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ECONOMIC EFFECTS OF
PROPULSION SYSTEM TECHNOLOGY
ON
EXISTING & FUTURE TRANSPORT AIRCRAFT

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FOREWARD

The following report presents the results of a detailed analysis of current propulsion system maintenance costs directed at determining the trends in costs with advances in engine technology. For this study, it has been necessary to project the maintenance costs of the JT9D-3A to levels consistent with a mature engine to provide a suitable basis for comparisons with the JT3D-1/3B and JT8D-1/7/9 propulsion systems.

During the introduction of the first JT3D-1 and JT8D-1 powered aircraft very high engine maintenance costs were experienced due to poor initial engine reliability. The early service experience with the JT9D-3A has followed the same trend of high costs. On each new engine program and irrespective of the manufacturer, it has been necessary to undergo substantial modification programs to overcome poor initial engine reliability. The cost of the programs has been mutually supported by the airline and the manufacturer. For the purpose of projecting JT9D-3A costs, the improved reliability of the modified/upgraded JT9D-3A and JT9D-7 engines has been used as guides. The initial JT3D-3B and JT8D-9 reliability experience and reduced maintenance costs fully support this approach.

In the course of this study, it has become apparent that with each new generation of commercial engine—in terms of dollars per hour of maintenance cost per 100,000 dollars of engine purchase price during the first years of service—substantial reductions in the relative impact of this early unreliability has been obtained.

The intent of this report is to provide a basis for defining in proper perspective, the maintenance cost impact of past steps in propulsion system technology; and to serve the industry and NASA as a point of

departure for new research efforts and new development programs.

The maintenance cost prediction methods developed by this study are felt to be improvements over the ATA method. The short form method follows the trends established by the newer engines more closely than the ATA method, and would be expected to predict more reasonable maintenance cost values for advanced engines. The long form method provides a convenient means of identifying the sections and cost elements of advanced engine designs that are most in need of improvement. These prediction methods must be applied carefully to avoid the pitfalls of the empirical correlation technique on which they, of necessity, are based. The correlation is based on detailed study of three different engine models, designed and developed by one engine manufacturer. Studies of two other engines by American Airlines on the same basis, however, support the trends developed. The maintenance cost information represents the experience of only one airline, but has been found representative of the entire fleet. Application of the methods to an advanced engine tacitly assumes that the evolutionary trends of engine design, development, operation and maintenance technologies established by the engines studied will be continued in the advanced engine. Hopefully significant breakthroughs in any of the areas identified could result in lower maintenance costs than predicted. Shift in emphasis among the major engine design requirements (fuel consumption, weight, cost and maintenance cost) based on general economic conditions, could result in error in the predicted maintenance cost.

The long form prediction method can be improved through additional work, especially in those modules and cost elements that contribute most to the total maintenance cost. A detailed investigation of the life of the critical parts and the reason they are finally scrapped is needed to permit the design of better parts and to estimate the life of the new designs. Also, the empirical correlations of this study should be updated from time to time as additional experience is accumulated with the current high-bypass-ratio engines and with other new engines as they are introduced. Such improvements will then permit realistic appraisal of the maintenance costs of future generations of advanced engines.

This work presents the results of the complete four Task Study Program. The work statement for each task of the program is set forth below.

STATEMENT OF WORK

General

The contractor shall perform all the required work to accomplish the tasks listed below. The contractors shall utilize data previously developed in the course of their advanced engine and transport aircraft studies in the conduct of this work.

Task 1: Collection, Preparation and Analysis of Current Propulsion System Costs

The contractor shall prepare and analyze current JT3D/707, JT8D/727/737 and JT9D/747 economic data to serve as the basis for projecting the operated costs of advanced technology propulsion systems. This analysis shall include determination of current propulsion system prices to the component level and beyond where appropriate and the cost for maintaining the propulsion system in airline service. Included with this analysis will be the estimated cost impact of unreliability and separation of costs of maintenance into material and labor categories. The data shall be prepared in a manner such that trends and directions with respect to complexity, performance, accessibility, materials, or other suitable parameters is presented.

Task II: Preparation and Analysis of Estimated Operating Costs for a 1979 Advanced Technology Engine as Installed in the Base Line Aircraft

The Contractor shall prepare estimates of the direct and indirect

operating costs of the engine and its associated installation on a representative advanced subsonic transport aircraft to be selected by the contractor. This estimate shall include the normal write-off of development costs in estimating propulsion system prices. The estimated spare engine, parts, reversers, etc. to support the engine in airline service shall be determined. The estimated cost for maintaining the total propulsion system in accordance with airline standard practice shall be developed. The Direct and Indirect operating costs of the total aircraft shall be determined and reported, with the propulsion system elements specifically defined.

Task III: Preparation and Analysis of the Base Line Design by the ATA 1967 Method for Direct Operating Costs and the Lockheed Method for Indirect Operating Costs

The estimated direct and indirect costs per standard methods shall be determined. The differences between the Standard method estimate of propulsion system direct operating costs and the cost developed in Task II shall be analyzed. Recommendations based on these findings shall be prepared in the form of suggested changes in the DOC formulation.

Task IV: Parametric Analysis of the Economic Effects of Major Propulsion System Design Features

Utilizing the data developed in Task II the general applicability of the improved DOC formula will be assessed. Recommendations as to the areas of propulsion technology which should be pursued to obtain improvements in engine operating economics will be prepared. Included with these recommendations shall be a description of the specific goal/objective sought and the magnitude of the economic benefit that would result if the suggested goal/objective were achieved.

TABLE OF CONTENTS

	<u>Page</u>
SUMMARY	1
CONCLUSIONS	2
I INTRODUCTION	6
A. Objectives	9
B. Approach Used in Analysis	9
II BACKGROUND	12
A. General Trends of Powerplant Maintenance With Service Use	12
B. Cost Per Hour Versus Years in Service	15
C. Fundamentals in Engine Maintenance Cost	17
1. Maintenance Program Philosophy and Cost Impacts	18
2. General Trends of Total Removal Rates Vs. Time	24
3. Cost of Repair Vs. Years in Service	26
4. Maintenance Cost Elements Vs. Time	27
5. Engine Maintenance Labor Elements in Engine Repair	29
6. Engine Maintenance - Material Consumption	30
7. Engine Maintenance - Outside Service	33
8. Airline Cost Accounting Methods	36
Figures for Section II	39-46
III DATA ANALYSIS AND TRENDS	47
A. Introduction	47
B. Basic Engine Total Maintenance Cost and Trends	48
C. Engine Maintenance Labor Cost	50
1. Maintenance Labor Cost for Complete Engine	51
2. Breakdown of Labor Cost by Module	53
D. Engine Maintenance Material Cost	59
1. Maintenance Material Cost for Complete Engine	60
2. Breakdown of Material Cost by Module	61
E. Installation Maintenance Cost Trends	64
1. Powerplant Package Maintenance Cost	64
2. Distribution of Powerplant System Maintenance Costs	66
3. Powerplant Installation Costs	67

TABLE OF CONTENTS - cont'd.

F. Dispatch Reliability	71
1. Introduction	71
2. Interruption Rates	71
3. Interruption Costs	72
APPENDIX I to SECTION III	75
Figures for SECTION III	84-157
IV TASK II - Analysis of Estimated Operating Costs for a 1979 Advanced Technology Engine as Installed in the Base Line Aircraft	158
A. Introduction	158
B. Background	158
1. Airplane Operational Scenerio	159
2. Baseline Airplane Description	162
3. Maintenance Philosophy	170
a. STF-429 Engine Maintenance Philosophy	170
b. Aircraft Maintenance Philosophy	172
4. STF 429 Engine Description	175
5. Power Plant Installation	178
C. Operating Economics/Costs	183
1. Introduction	183
a. Depreciation of Investment	183
b. Fuel Cost	184
c. Maintenance Costs	185
2. Depreciation of Investment	185
a. Purchase Price of Aircraft & Installed Engines	185
b. Power Plant Spares Support Investment	187
c. Facilities Investment	200
d. Tooling/Equipment Investment	204
e. Depreciation of the Investment in Equipment, Spares and Support	209
3. Fuel Cost	212
4. Propulsion System Maintenance Cost	213
a. Estimated Mature Propulsion System Costs	213
1. Power Plant Installation - Build up of costs	215
2. Basic Engine Build up of Costs	223
3. Total Predicted Mature Propulsion System Maintenance Cost	232
b. Maintenance Cost-First Five Years	248
1. Power Plant Installation	248
2. Basic Engine	250
3. Predicted Average Propulsion System Maintenance Cost in Early Service	253
5. Summary of Predicted Propulsion System Direct Operating Cost per Aircraft Operating Hour	254

TABLE OF CONTENTS - cont'd

D.	Dispatch Reliability Impact	255
E.	Comparison with Actual Experience of Current Propulsion Systems	258
V	TASK III - Preparation and Analysis of the Base Line Design by the ATA 1967 Method for Direct Operating Costs and Lockheed Method for Indirect Operating Cost	267
A.	Introduction	267
B.	Update of ATA-1967 D.O.C. Method Coefficients	269
C.	Analysis of Base Line Design	272
1.	Direct Operating Costs	272
a.	Engine Maintenance Cost Comparisons	273
b.	Depreciation Cost Comparison	274
c.	Fuel Cost Comparison	276
2.	Indirect Operating Costs	276
D.	Recommendations for New Methods of Forecasting Propulsion System Maintenance Cost	278
1.	Introduction	278
2.	Recommended Methods	279
VI	TASK IV - Parametric Analysis of the Economic Effect of Major Propulsion System Design Features	288
A.	Introduction	288
B.	Impact of Propulsion System Maintenance Cost on Overall Aircraft Operating Cost	288
C.	Assessment of General Applicability of the Recommended New Methods of Forecasting Propulsion System Maintenance Cost	292
D.	Recommended Areas of Propulsion System Technology which Should be Pursued to Obtain Improved Operating Economics.	297
1.	Initial Purchase Cost	298
a.	Value of Design Alternatives	298
b.	Power Plant Installation	299
c.	Basic Engine	303
2.	Continuing Cost of Maintenance	303
a.	Engine Installation	305
1.	Labor Costs	306
2.	Reverser Cost	307

TABLE OF CONTENTS - cont'd

b.	Basic Engine	308
1.	HP Turbine Module	309
2.	LP Turbine & HP Compressor	310
3.	Combustor	311
4.	Controls	311
3.	Dispatch Reliability Costs	314
4.	Fuel Costs	316

LIST OF FIGURES & TABLES
(Section II)

Figure	Title	Page
II-1	Total Maintenance Cost per Engine Flight, Hour vs. Time	39
II-2	Maintenance Program Engine Removal Rate vs. Time	40
II-3	Engine Removals for Overhaul and Repair vs. Time	41
II-4	Total Maintenance Cost per Repair vs. Time	42
II-5	Maintenance Cost Elements vs. Time	43
II-6	Engine Removal Cycle Labor Elements	44
II-7	Outside Services Costs	45
II-8	Cumulative Capital Investment in Tooling	46

LIST OF FIGURES & TABLES
(Section III)

Figure	Title	Page
III-1	Total Maintenance Cost of Complete Powerplant	84
III-2	Typical Mature Powerplant Maintenance Breakdown	85
III-3	Reduction of Total Maintenance Cost of Basic Engine With Maturity	86
III-4	Total Maintenance Cost Normalized to Engine Price	87
III-5	Cost Per Repair Increase to Mature Level	88
III-6	Cost Per Repair Normalized to Engine Price	89
III-7	Removal Rate Improves to a Mature Level	90
III-8	Mean Time Between Engine Removals Increases With Flight Length	91
III-9	Maintenance Labor Cost Decreases as the Engines Mature	92
III-9A	Maintenance Labor Cost Decreases to Mature Level	93
III-10	Manhours Per Engine Flight Hour Normalized for Engine Price Shows the JT9D at a Substantially Lower Rate Than the JT3D and JT8D	94
III-11	Manhours Per Repair Increases to Mature Level	95
III-12	When Normalized for Engine Price, the JT9D Exhibits Significantly Lower Manhours Per Repair	96
III-13	Contribution of Engine Sections to Total Manhours Per Engine Flight Hour	97
III-14	Relative Contribution of Engine Sections to Manhours/Engine Flight Hour	98
III-15	JT3D Engine Cross Section With Engine Sections Identified	99
III-16	JT8D Engine Cross Section With Engine Sections Identified	100
III-17	JT9D Engine Cross Section With Engine Sections Identified	101

LIST OF FIGURES & TABLES
(Section III - cont'd.)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
III-18	Compressor Manhours Per Repair Increase With Increasing Tip Speed, Size and Complexity	102
III-19	Design and Construction Techniques Have Significant Impact on Manhours per Repair for the Diffuser Case	103
III-19A	Combustor Manhours per Repair Increase with Size and Complexity	104
III-20	Turbine Manhours per Repair Increase with Increasing Temperature, Size and Complexity	105
III-21	Low Compressor Mean Time Between Repair Adjusted for Flight Length	106
III-22	High Compressor Mean Time Between Repair Adjusted for Flight Length	107
III-23	Mean Time Between Repairs of the Diffuser Case is Close for All Three Engines on an Adjusted Basis	108
III-24	Combustor Mean Time Between Repair Adjusted for Flight Length	109
III-25	High Turbine Mean Time Between Repair Adjusted for Flight Length	110
III-26	Low Turbine Mean Time Between Repair Adjusted for Flight Length	111
III-27	Compressor Mean Time Between Repair Adjusted for Flight Length	112
III-28	Combustor Mean Time Between Repair Adjusted for Flight Length	113
III-29	Turbine Mean Time Between Repair Adjusted for Flight Length	114
III-29A	Experience Indicates that Mean Time Between Engine Removals is 83% of Minimum Module M.T.B.R.	115
III-30	Maintenance Material Cost Decreases as the Engines Mature	116
III-31	Maintenance Material Cost Normalized for Engine Price Shows the JT9D at a Lower Rate than the JT3D and JT8D	117

LIST OF FIGURES & TABLES
(Section III - cont'd.)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
III-32	Maintenance Material Cost per Repair Reaches a Mature Value Quickly	118
III-33	Maintenance Material Cost per Repair Spread is Reduced by Normalizing for Engine Price	119
III-34	Contribution of Repairables, Expendables and Life Limited Parts to Maintenance Material Cost	120
III-35	Contribution of Engine Module Sections to Total Maintenance Material Cost	121
III-36	Relative Contribution of Engine Module Sections to Total Maintenance Material Cost	122
III-37	Description of Prime High Cost Parts Included in Modules	123
III-37A	Module Material Cost per Repair Normalized by Module Price Are Essentially Constant Between Engines	124
III-38	707-123B Direct Maintenance Cost	125
III-39	727 Direct Maintenance Cost	126
III-40	747 Direct Maintenance Cost	127
III-41	707-123B Direct Maintenance Cost	128
III-42	727 Direct Maintenance Cost	129
III-43	747 Direct Maintenance Cost	130
III-44	Engine Labor	131
III-45	Engine Material	132
III-46	Powerplant Systems - Line Maintenance	133
III-47	Powerplant Systems - Shop Maintenance	134
III-48	Powerplant Systems - Shop Material	135
III-49	Powerplant Systems - Outside Services	136
III-50	Powerplant Systems - ATA 71 Powerplant	137
III-50A	Powerplant Systems - ATA 71 Powerplant	138
III-51	Powerplant Systems - ATA 71 Powerplant	139
III-51A	Powerplant Systems - ATA 71 Powerplant	140
III-52.	Powerplant Systems - ATA 78 Reversers	141

LIST OF FIGURES & TABLES
(Section III - cont'd.)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
III-53	Powerplant Systems - ATA 78 Reversers	142
III-54	Powerplant Systems - ATA 80 Starting	143
III-55	Powerplant Systems - ATA 80 Starting	144
III-56	Powerplant Systems - All other ATA's	145
III-57	Powerplant Systems - All other ATA's	146
III-58	Mechanical Schedule Reliability History	147
III-59	Powerplant Systems	148
III-60	707 Interruption Rate	149
III-61	727 Interruption Rate	150
III-62	737 Interruption Rate	151
III-63	747 Interruption Rate	152
III-64	Powerplant Systems - Interruption Costs	153
III-65	707 Powerplant Systems - Interruption Costs	154
III-66	727 Powerplant Systems - Interruption Costs	155
III-67	737 Powerplant Systems - Interruption Costs	156
III-68	747 Powerplant Systems - Interruption Costs	157

LIST OF FIGURES & TABLES
(Section IV)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
IV-1	Flight Profile	161
IV-2	Baseline Airplane Configuration	164
IV-3	Block Fuel and Block Time	167
IV-4	Airplane Sensitivity to Engine Weight	168
IV-5	Airplane Sensitivity to Specific Fuel Consumption	169
IV-6	STF-429 Engine Configuration	177
IV-7	Engine Installation	179
IV-8	Rate of Investment in Shop Support Spares to Investment in Installed Powerplants	198
IV-9	STF 429 Spares Investment Levels versus Fleet Build-Up	199
IV-10	Effect of Fuel Price on Direct Operating Cost	
IV-11	Predicted Engine Change, Build-up & Teardown Manhours	218
IV-12	Engine Change Time Analysis	219
IV-13	Engine Labor	220
IV-14	Engine Material	221
IV-15	STF-429 Engine Parameters Needed for Predicting its Maintenance Cost	233
IV-16	Average Manhours per Repair JT3D, JT8D, JT9D, & STF 429	234
IV-17	Manhours per Repair for STF-429 Fan & High Compressor	235
IV-18	Manhours per Repair for STF-429 Diffuser Section	236
IV-19	Manhours per Repair for STF-429 Combustor Section	237
IV-20	Manhours per Repair for STF-429 High & Low Turbine	238
IV-21	Mean Time Between Repair JT3D, JT8D, JT9D and STF-429	239
IV-22	Mean Time Between Repair STF-429 Fan and High Compressor Modules	240

LIST OF FIGURES & TABLES
(Section IV - cont'd.)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
IV-23	Mean Time Between Repair for STF-429 Combustor Section	241
IV-24	Mean Time Between Repair for STF-429 High & Low Turbine Modules	242
IV-25	STF-429 Manhours per Engine Flight Hour	243
IV-26	Maintenance Material Cost per Repair/Price for the STF-429 Modules	244
IV-27	Estimated Maintenance Material Cost per Engine Flight Hour	245
IV-28	STF-429 Total Basic Maintenance Cost and Mean Time Between Engine Removal - Mature Engine	246
IV-29	Total Maintenance Cost Sensitivity - STF-429	247
IV-30	STF-429 Total Basic Engine Maintenance Cost and Mean Time Between Engine Removal 1st 5 Years	252
IV-31	Mechanical Schedule Reliability	256
IV-32	Comparison of Estimated STF-429 Manhours per Repair with JT3D, JT8D & JT9D Experience	260
IV-33	Comparison of Estimated STF-429 Engine Removal Rate	261
IV-34	Comparison of Estimated STF-429 Maintenance Material Cost per Engine	262
IV-35	Comparison of Estimated STF-429 Manhours per Engine Flight Hour	263
IV-36	Comparison of Estimated STF-429 Maintenance Material Cost	264
IV-37	Comparison of Estimated STF-429 Maintenance Material Cost per Repair	265
IV-38	Comparison of Total Estimated STF-429 Maintenance Cost per Engine Flight Hour	266

LIST OF FIGURES & TABLES
(Sections V & VI)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
V-1	Engine Labor	285
V-2	Engine Material	286
VI-1	Value of Design Improvements	300
VI-2	Value of 10% SFC Improvement	301
VI-3	Value of 10% SFC Improvement	302
VI-4	Propulsion System Cost Impact	304
VI-5	Direct Operating Cost-Sensitivity to Propulsion System Variable	304a

LIST OF FIGURES & TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
IV-1	Operational Model	160
IV-2	Model D4-179(c) Principal Characteristic	165
IV-3	Weight Statement Model D4-179(c)	166
IV-4	Scheduled Maintenance Check Assumptions	174
IV-5	STF-429 Powerplant Spares Support Ground Rules	192
IV-6	STF-429 Powerplant Spares Support	194
V-1	Direct Operating Cost Level Basis	270
V-2	Formula for Operating Costs	271
V-3	Direct Operating Cost for D4-179C/STF 429	273
V-4	Comparison of STF-429 Maintenance Cost - Mature Level	274
V-5	Comparison of STF 429 Maintenance Cost - Initial Operation	275
V-6	Basic Engine Maintenance Cost Forecasting	280
V-7	Basic Engine Maintenance Cost Forecasting	281
V-8	Basic Engine Maintenance Cost Forecasting	282
V-9	Propulsion System Direct Maintenance Cost	287
VI-1	Methods Comparison	294
VI-2	Methods Comparison	295
VI-3	Methods Comparison	296
VI-4	Methods Comparison	296a
VI-5	Total Maintenance Cost Sensitivity	313

GLOSSARY OF TERMS

Terminology used in this report departs from industry standard definitions where required by more explicit usage.

aging effects. gradual degradation of physical conditions resulting from repeated applications of stress cycles

ATA System - also ATA system codes. Air Transport Association, airline industry standard separation of the airplane systems and their components into coded groupings

attrition. a low level of loss (and hence need for replacement) of parts due to normal wear, mishandling, neglect, accidents, etc.

CAB Direct Maintenance Cost File. Civil Aeronautics Board Computer File of Direct Maintenance Costs as reported by all U.S. airlines in accordance with CAB definitions; contains breakdown into material, labor, outside services by "engine", "airframe" and "other" categories; CAB Form 41, standardized format for making computer file inputs on maintenance costs, traffic and capacity statistics

campaign modification - also campaign repair. required maintenance action applicable to all members of a designated family of units within specified time constraints

cancellation (i.e. flight cancellation). non-operation of a scheduled flight

component. an element of a power plant or engine customarily treated, or capable of being treated, as an entity

delay (i.e. flight delay). the time difference between the actual departure time and that shown in the published time table

dispatch reliability. an index of the average performance of a fleet of airplanes in terms of consistency of flight departures at the times scheduled in the published time tables

engine-basic. the bare engine produced and assembled by the manufacturer plus associated components he supplies to make it adaptable to the airplane installation

escalated cost - also "1972 dollars". a mathematical adjustment to maintenance costs of prior years in order to make their results equivalent to those of 1972

FAA. Federal Aviation Administration. an agency of the federal government created by act of Congress to regulate civil aviation

FAA Certification. attestation by the FAA that a unit of flight equipment has met all physical requirements contained in applicable FAA regulations

facility-maintenance. a plant consisting of hangars, buildings, shops, machine tools, jigs, fixtures, stores and trained personnel organized to perform maintenance on flight equipment

flight hours-engine/airplane. the accumulation of operating time intervals beginning at the start of a flight when the airplane wheels leave the ground and terminating when the wheels again contact the ground

hardware. miscellaneous, aeronautical-grade small parts such as bolts, nuts, studs, washers, etc. (sometimes corrupted to include general external parts such as pipes, tubes, brackets, braces, sheet metal parts, etc.)

in house. maintenance work performed by an airline using plant facilities which it owns or over which it exercises total management control

inspection. a visual condition check (with or without supporting equipment/instrumentation) against specific physical criteria

installation. the power plant components installed on the basic engine by the airplane manufacturer constituting the interfaces between the airplane and the propulsive system

labor-direct. the cost of labor comprised of the product of the man hours expended and a pay rate reflecting that paid to the mechanic (normally adjusted only for the effects of work shift differential pay and overtime pay)

labor-fully allocated. the sum of direct labor and overhead in terms of facilities rental, equipment depreciation, benefits, supervision, training and other support costs attendant to maintaining the work force

lead time. time interval in advance of need date required for ordering parts, activating facilities or other preparations for future requirements

life limited part. an engine part, usually a rotating element, restricted to a maximum number of engine hours or stress cycles by the FAA on the basis of manufacturer's test data. In addition, the airline may establish additional limits of its own

maintenance. expenditure of physical effort and consumption of material in the activities of servicing, repairing and restoring flight equipment

maintenance cost. monies spent for labor, materials and contractor fees to service, repair and restore flight equipment

maintenance-line. maintenance performed at an outlying station on an airline's route structure as opposed to that performed at its principle maintenance base or shop

maintenance-on wing. maintenance accomplished on the power plant while attached to the airplane

maintenance-shop. maintenance performed at a specialized facility containing machine tools, test facilities, trained personnel and material stores with capability for all phases of repair and restoration

mature engine. one in service for an airline (or the industry) for sufficient time to have progressed beyond early development problems and to have been afforded stabilized operational and maintenance management

mechanical schedule reliability. an index of the mechanical performance of a fleet expressed as the percentages of time the fleet operates in accordance with the published time table (schedule impacts in any categories other than "mechanical" are excluded in computing this index)

module. a combination of assemblies, sub assemblies and parts contained in one package, or so arranged as to be installed in one maintenance action

NHA. Next Higher Assembly. The group of parts constituting a physically manageable unit to which the specific part is added in the normal assembly sequence

overhaul. major maintenance action having as its objective the restoration of a unit of flight equipment to a high condition level approaching its original characteristics

outside services. maintenance work performed for an airline by the manufacturer, a maintenance contractor or other support agency for a fee

part. the smallest sub division of a power plant, engine, module or component normally achieved in the disassembly process; expendable, non-reusable due to cost of repair exceeding cost of replacement; repairable, capable of successive restorations to an acceptable condition level through formal processes; rotable, routinely exchanged between the repair shop and another shop or line station wherein a serviceable unit is delivered and a unit requiring repair is received

power plant - also power package, QEC. the engine and engine associated equipment removable as a unit from the airplane

program-maintenance. the plan established to control all phases of servicing, repair and restoration of flight equipment; CMM, Condition Monitored Maintenance, continuous surveillance of a comprehensive set of power plant condition indicators in order to apply maintenance action commensurate with demonstrated need; O/C, on condition, the periodic check of specified condition indicators at rigid intervals with immediate corrective action applied to any anomalies revealed (sometimes corrupted to mean operation without deliberate condition checks and application of

maintenance action only when a power plant fault reveals itself); overhaul, application of the overhaul process to the total power plant at rigid time intervals; SSV, Scheduled Shop Visit, periodic maintenance characterized by rigid time intervals and restoration of selected portions of all power plants via a fixed bill of work to specified condition standards

QEC. Quick Engine Change - also power plant/power package. the engine and engine mounted equipment removable as a unit from the airplane (sometimes corrupted to mean "installation")

removal. detachment of a power plant from an airplane, also detachment of a component from a power plant; scheduled, preplanned removal of a serviceable unit because of maintenance program requirements; premature, removal for evidence or suspicion of physical/performance failure; convenience, removal of a serviceable unit for miscellaneous causes not associated with a physical fault or maintenance program

repair. the correction of a mechanical fault(s) to restore the function of a power plant, engine, component or part

restoration - also reconditioning, renovation, refurbishment. the maintenance activity involved in preparing a power plant, engine, component or part for continued reliable operation subsequent to its having been operated through a specified number of stress cycles or hours or to have reached a specified physical condition

schedule interruption - mechanical. a mechanical discrepancy occurrence which prevents an airplane from departing, completing its flight and arriving at its destination in accordance with the published time table

servicing. scheduled maintenance applied to flight equipment consisting of lubrication, fluid replenishment, cursory inspection, periodic adjustment, etc.

shop. 1. a specialized facility containing machine tools, test facilities, trained personnel, material stores and associated support functions for the repair and restoration of flight equipment; 2. a sub-shop within the facility designated for division of work and/or cost accumulation

shop visit. the induction and processing of flight equipment through a shop

Time Between Overhauls (TBO) - also Allowable Time Between Overhauls. maximum flight equipment operating time intervals allowable between successive major restorative maintenance

troubleshooting. determination of the cause of malfunctioning flight equipment through inspection, test, simulation or other physical activities

utilization. 1. airline application of an airplane type to specific service; 2. the portion of an airplane's/fleet's potential operating capacity actually scheduled or achieved

vendor. supplier of bulk material, hardware and common aeronautical-grade parts (sometimes corrupted to mean any outside supplier of material and services including the manufacturer and maintenance contractors)

volume. the quantity of units processed during a stated time interval

warranty. a formal commitment by a manufacturer, maintenance contractor or vendor to make specified restitutions in case of certain deficiencies in his product or service

SUMMARY

This report presents the results of a four (4) task study of the economic effects of propulsion system technology on existing and future transport aircraft.

Task I, Sections I, II and III of this report, present the results of a detailed analysis of historical propulsion system maintenance costs as experienced by American Airlines. Section IV presents an analysis of the estimated maintenance cost of an advanced technology propulsion system representative of a power plant which could be certified in the 1979 time period. This analysis, undertaken as Task II of the subject study, presents estimated maintenance and logistic support costs based on a preliminary design for an advanced engine. Task III, presented in Section V, presents a comparison of the aircraft's direct operating cost impact as determined by the 1967 Air Transport Association costing procedures as set forth in ATA 100 and the estimated cost determined in the preceeding analysis. Revised maintenance cost estimating procedures were developed which more accurately predict the maintenance cost of future as well as current propulsion systems. Two forms of the prediction methodology are presented. The long form, more detailed, is most suitable for advanced design studies by manufacturers. The second or short form is suggested as a replacement to the engine maintenance cost equations as set forth in the ATA Specification 100 as updated annually by the various manufacturers from CAB Form 41 data.

Task IV presents the results of a parametric analysis of the economic effects of major propulsion system design features and recommendations concerning areas where advanced research efforts could yield reduced propulsion system operating costs.

This report was prepared by American Airlines with the aid of the Boeing Commercial Airplane Co. and the Pratt & Whitney Division of United Aircraft Corporation as subcontractors. The major objective of this study was to identify the impact of engine technological advancement on propulsion system operating costs and in particular, maintenance costs for the purpose of identifying trends which could bring technology to bear on opportunities to reduce such costs. The equations presented for estimating engine maintenance cost are believed reasonably accurate and suitable for the purpose of providing guidance in the selection of advanced propulsion system design variables and the areas where propulsion system maintenance cost can be reduced or controlled.

CONCLUSIONS

The following conclusions have been drawn from the studies reported herein:

1. There is a definite maintenance cost versus operating time history for commercial engines which each new engine tends to follow. The general cyclic history of maintenance cost are remarkably similar for all of the different engines studied. This history can be broken into two periods - the "Introductory" period which lasts about 5 years and a "mature" period which follows. The introduction period is marked by a propulsion system maintenance cost that averages approximately twice the average hourly maintenance costs during the latter years of more mature engine operation. The high costs encountered in the introduction on each new technology propulsion system into service is quantifiable and deserves attention.

2. Engine maintenance costs have been historically presented as cost per operating hour. The maintenance cost per hour is the product of the average cost to repair engines removed from service during a particular period, multiplied by the quantity of engines removed from service for repair per aircraft or engine operating hours for cause - either due to failure or the need to replace a life limited part or component. These two factors - the average cost to repair versus time - and the propulsion system repairs required per unit of operating time, provide the fundamental variables to be addressed in future technology programs.
3. Past steps in propulsion technology have on a relative basis, resulted in lower relative maintenance costs. On the basis of maintenance cost per hour per unit of engine purchase price ($\$/\text{Hr}/\$ \text{ of price}$), each new engine has been less expensive to maintain. On an absolute basis however, the maintenance costs of propulsion system are higher for the more advanced engines due to their higher prices.
4. Commercial engines which were derivatives of military engines do not show reliability or maintenance cost reduction trends sufficiently different, over the long term, to warrant insistence upon previous military core engine experience as a precondition for commercial transport engine programs.
5. The power plant package design has a significant impact on propulsion system maintenance costs. The complexity of the installation reflects directly on the labor expended to mount, strip,

rebuild and remount the equipment and parts necessary for engine installation as well as the repair of such parts. The maintenance cost, both labor and material, for installation maintenance can vary between 12 and 31% of the total maintenance costs. The costs for installation maintenance are improved by fan case mounting of the gearbox and the engine and aircraft accessories as typified by JT8D/JT9D-20 and CF6 engines and their installation on 727/DC-9/737 and DC-10. Installation design and complexity has double leverage in total operating costs. Spare costs are impacted by the installation design, particularly the installation buildup kit (Q.E.C.) as well as the labor required to repair engines since the items must normally be removed to accomplish the repair.

6. Examining maintenance cost data from a number of perspectives and in constant year dollars, changes general industry preconceived notions as to the relative position of the various engines and their maintenance costs. This approach provides a clearer perspective on the real changes in costs resulting from introduction of new technology propulsion systems.
7. The role of labor costs in overall propulsion system maintenance cost is considerably more important than previously acknowledged. The traditional use of direct rather than fully allocated labor costs as required by CAB is the cause.

8. The cost of expendable materials (non-repairable parts, nuts, bolts, gaskets, seals) replaced per repair is larger than has been recognized and warrants treatment in advanced engine designs.
9. Great opportunities exist to improve propulsion system total operating cost as described in Section VI of this report. The initial purchase price of engines versus their performance needs careful attention. Opportunities to reduce costs by improving early engine reliability, reduced installation complexity, longer parts' lives, improved controls and subsystems and improved repairability, offer equal and challenging objectives for future technology programs.

The reduction in fuel consumption remains an important target but must be considered in the light of total propulsion system economics.

10. This analysis has provided valuable insight into the cost impact of advanced technology propulsion systems. The equations and methods developed for predicting costs are greatly improved over current methods. These methods, however, are not absolutes and will undoubtedly be questioned. This process is desirable and improvements should be expected. measure of success of such an effort is the rapidity with which the industry by technological change and deeper insight, makes the analysis and conclusions presented obsolete.

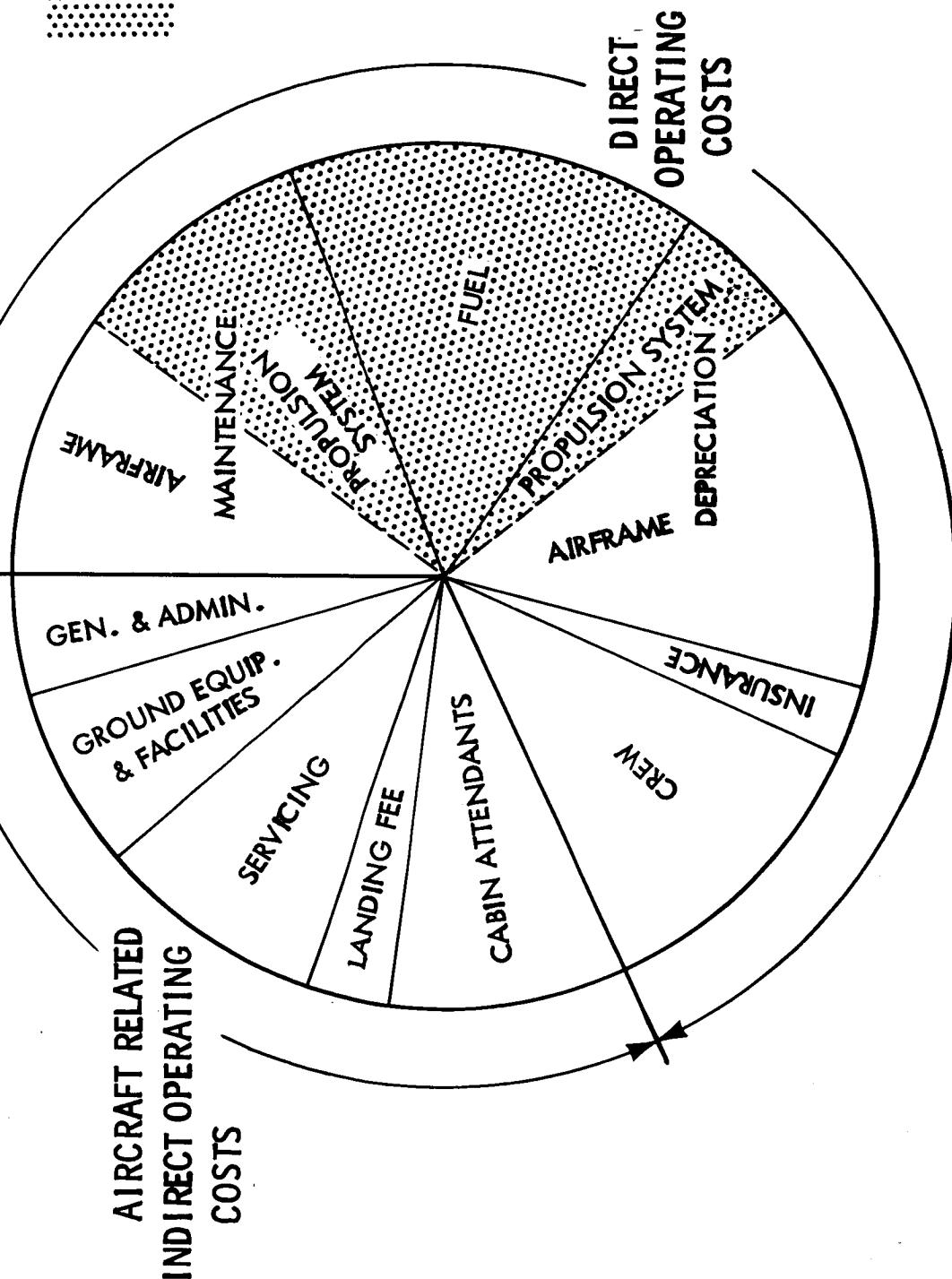
I. INTRODUCTION

The purpose of this report is to present the results of a detailed analysis of current engine maintenance costs which can serve as the basis for projecting the maintenance costs of new and more advanced technology engines. This effort was undertaken to develop an improved methodology for estimating the cost of maintaining engines in airline service. It has become apparent that the 1967 ATA "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes" is unsatisfactory for projecting the impact of advanced technology propulsion systems on airplane direct operating cost of aircraft of the same basic type and technology. However, its use has been expanded, due to the lack of a suitable recognized substitute, to encompass comparison of widely different aircraft and engine types and technologies. The ATA method has also been employed in attempts to provide guidance as to where advanced research efforts might be most cost effectively applied. For both purposes, the ATA procedure is too crude to provide reliable guidance and its application is in fact, resulting in grossly misleading conclusions.

Of those costs typically classified as airplane direct operating costs (DOC), three are directly dependent upon engine performance, design and reliability: these are the cost of fuel, engine acquisition and resulting maintenance. In 1973, for a typical wide-body transport, these costs accounted for more than 40% of the aircraft's DOC. Of this 40%, 55% is attributable to fuel cost, 30% to maintenance, and 15% to engine acquisition. Indirectly, engine weight, fuel consumption and geometric characteristics play a significant role in determining the size, and hence the economics, of the entire airplane.

OPERATING COSTS

DIRECTLY
PROPULSION
SYSTEM RELATED



This engine/airframe interaction occurs mainly in the "rubber" or preliminary design phase of both the engine and airframe. The role of acquisition and maintenance cost during this "rubber" phase is the same as it would be for an existing aircraft, but has been less significant relative to engine performance and geometric characteristics.

The fuel cost element of DOC is relatively easy to determine through the use of established computerized aircraft simulation techniques. The difficulties in this area are in the prediction of installed engine performance, and currently in what fuel price to use.

The propulsion part of aircraft acquisition costs has traditionally been over 20% of the investment in flight equipment. An accurate prediction of the spares requirement includes knowledge of fleet size, geographic considerations, route structure, pooling agreements and fleet commonality. Each airline, therefore, has slightly different levels of spares based on the above as well as engine complexity and maturity.

An accurate prediction of engine price is perhaps more difficult. Engine price is only partially dependent upon those performance and physical characteristics that are capable of being determined analytically. Factors such as competitive posture and business level projections are the most difficult to predict and are perhaps the most significant predictions involved in price estimation. Most techniques (e.g. Rand Method) do not address this aspect of price estimation. Additional discussion on these items will be found in latter sections of this report.

As stated earlier, 30% of the engine's direct contribution to DOC on a typical aircraft is attributable to maintenance. On a mature airplane, the engine and airframe have contributed equally to total maintenance cost (engines bear a larger portion of the materials cost; the airframe requires more labor). Engine maintenance cost is then as important as that of the airframe, and if the indirect cost of reliability (delays and

cancellations) attributable to the engine are added, the significance of engine maintenance and reliability approaches that of fuel consumption (at historical price levels).

A. Objectives of Study

The direct operating cost impact of the entrance of the new high bypass generation of engines into airline service was not reliably forecast by the application of the ATA methodology, and the benefits of the greatly improved specific fuel consumption have unfortunately been over-shadowed by the unexpected higher maintenance costs experienced with these higher technology engines.

Because of the increased maintenance costs associated with the higher bypass ratio engines, airlines have become concerned that technology has been pushed too far and that at least for the future, it would be more appropriate to perhaps back-up to more conservative technology levels. The current economic hardships and energy problems faced by the airlines have increased the need to more accurately assess the economic effects of propulsion system technology on existing and future transport aircraft. This is the precise objective of this effort.

B. Approach Used in the Analyses

It was deemed essential to developing an improved methodology for projecting engine direct operating costs to first study in detail the actual maintenance cost experience of several engines in airline service to provide the necessary understanding of where the costs were actually being incurred in maintenance of aircraft turbine engines. The question of "Is the experience of one airline typical of all airlines?" was immediately addressed by reviewing the CAB Form 41 reported engine main-

tenance costs of other airlines to insure that American's costs were typical. With the assistance of American's subcontractors, the Boeing Airplane Company and Pratt & Whitney Division of United Aircraft Corporation, this question has been satisfactorily answered in the affirmative.

The engine maintenance cost experience during the period 1968 thru 1972 has been analyzed in detail for the JT3D-707, JT8D-727, and JT9D-747 propulsion systems. In this analysis it was found desirable to retrieve and study engine maintenance cost records back to 1961 for the JT3D and to 1964 for the JT8D to cover the introduction into service periods for these engines. American has also analyzed the maintenance cost experience of the Spey engine for the period 1966 thru 1971 covering the full life of that engine in American's fleet and to the extent appropriate, the experience with the CF6-6D engines during its introduction into service. This was done to insure that characteristics of the JT3D, JT8D and JT9D with respect to their maintenance costs were not peculiar to the manufacturer, but did in fact, represent the impact of steps in engine technology. In this phase of the analysis no significant manufacturers' peculiar trends were found and the overall trend of maintenance costs with increasing complexity, as necessitated by higher pressure ratios and turbine inlet temperatures, was as expected. Engines of increasing complexity result in higher maintenance costs due both to the basic engine complexity as well as installation complexities. In general, modular construction offers offsetting benefits in labor costs, however, increasing complexity brings increased maintenance material costs.

The approach utilized in this analysis was to review the cost per engine flight hour divided into labor, material, and repairs of parts performed by, or contracted to, outside agencies known as Outside Service :

(OSS) over the years of study. The cost to repair an average engine was also analyzed, broken into labor, material and OSS over the years of study. The cost associated with the average engine repair was also subdivided into cost to repair the individual modules of the engine as a means to determine trends with complexity. The cost to repair the average engine module was also compared to the value of that module in the purchase price of a new engine (i.e., the cost to repair a high pressure compressor divided by the cost of the compressor as part of the purchase price of the engine). The impact of flight duration was also assessed by looking at the costs on a per flight basis.

Cost comparisons were made on an escalated basis such that all costs were evaluated in terms of 1972 year dollars. Labor costs were escalated on the basis of American Airlines actual labor rates for the study years and materials costs were escalated on the basis of a combined commodity and labor index normally used for such purposes.

Labor costs were treated in two ways both as direct labor and as fully allocated labor to insure full attention was given in the analysis to the importance of labor and increasing complexity.

To reiterate, cost data records for the various years were analyzed as is and in terms of 1972 dollars. Labor costs were studied both as direct and fully allocated costs. The analysis format was in terms of dollars per hour, dollars per repair, dollars per repair or hour divided by purchase price, and in dollars per flight cycle. In all cases the costs for labor, material, and OSS were studied individually as well as combined. The analysis was taken to the depth of specific assemblies or modules and to piece parts where further analysis appeared desirable.

II. BACKGROUND — AIRLINE PROPULSION SYSTEM MAINTENANCE

Fundamental in the discussion of engine maintenance costs is the need to project costs for the "mature" engine. Engines are developed and introduced into airline service at different times. In the early years of service, high maintenance costs are encountered due to unforeseen problems. Consequently, to determine the impact of technology, all cost comparisons must be made on the basis of mature engines. Because of the actual differences in costs brought about by differences in engine maturity or reliability at any point in time, comparing maintenance costs for engines long in service with those just entering service is technically incorrect and misleading. At the same time, changes in maintenance philosophy over the years have produced real changes in observed engine maintenance cost. The remainder of this section of the report is directed at a systematical discussion of the observed engine maintenance cost variations with time. A complete understanding of these effects is necessary since the development of the maintenance cost trends with technology presented in the latter section of this report were developed by factoring all engine experience to "mature engine" conditions and to constant maintenance philosophy.

A. General Trend of Powerplant Maintenance Cost with Service Use

Turbine engine powerplants in airline service experience variations in maintenance cost with time which, although differing in magnitude from model to model, follow the same general trends. The following briefly describes the cycle beginning with introduction of a new airplane/propulsion system into service through the maturing process. The introduction of a new airplane type is portrayed since it involves all facets of the process. New acquisition of an in-production airplane by an airline or modification of an existing type to meet specific mission requirements are real life situations but each follows the latter portions of the overall cycle.

1. Inception

A new airplane design starts as a two way dialogue between the airline's advanced planning group and the airplane company's marketing department. The airline may have carefully defined a "paper" airplane (passenger capacity, operating constraints, operating cost goals, etc.) which it needs for specific routes and with which it wants to have passenger appeal and high potential for operating profitability. It then approaches several airplane companies for preliminary proposals to be evaluated against the stated needs. On the other hand, an airplane company in search of future business may conduct its own evaluation of the market potential for an airplane to fulfill the widest possible airline needs and then approach several airlines with initial exploratory contacts. Potential engine suppliers are brought into the discussion at a very early date because of the profound effect of the engine upon airplane performance, cost, configuration options, delivery dates, etc. of concern to both the airplane company and the airline. Airline interests further include development status of the candidate engines; reliability; maintainability; short and long term maintenance and operating costs; compatibility with existing or planned fleets; and adaptability to existing or planned shops and support equipment. The final design offerings are achieved through an iterative process which attempts to achieve an optimum response to the airline requirements along with greatest airplane sales potential. Ultimate selection of the airplane/powerplant configuration occurs when the airline believes that the design constitutes an optimum physical/economic combination and the airplane and engine manufacturers believe that it offers an attractive business risk.

2. Powerplant Design Development

With the signing of the purchase contracts, the airplane and engine manufacturers and the airlines enter the next phase which is concerned with solidification of the design. The performance, operational and maintenance aspects are part of the design and development process. Maintenance costs have suffered in the past due to the emphasis placed on overall aircraft performance.

3. Maintenance Support Readiness

Simultaneously with the initiation of the design development phase, preparation for maintenance support of the engine and powerplant elements is undertaken. Since the airline is responsible for maintenance of the operational fleet, it normally leads this effort with major participation by the other two companies in a three-way, mutually supportive activity. The maintenance support program involves development of maintenance programs; instruction manuals; shop and line maintenance tooling/facilities; parts, engine and powerplant spares; and personnel training. The manufacturers supply inputs and assistance to the airline activities as well as providing for service organizations, continuing spares manufacturing capabilities and design improvement support. The continuing objective of this effort is to plan for the most cost effective approach to the powerplant's maintenance.

4. Early Operation

As the new airplane/powerplant enters service, the quality of the design and of the operational/maintenance preparations are put to the test. This is the time when maintenance cost tracking begins. Characteristically, design inadequacies are revealed which inflate

the early maintenance costs. These cost impacts are partially shared by the manufacturers through warranty provisions in the purchase agreements and through commitments to continuing product support.

4. Maturing Engine Phase

As the airline becomes proficient in the operation and maintenance of the powerplant and as original design deficiencies are corrected by the manufacturers, the maintenance costs trend downward. There may be zigzags in this curve due to changes in maintenance programs, further design problems revealed by longer term operation or changes in utilization of the airplane. Maintenance costs, characteristically, reach their minimums during this phase as a result of concentrated activities by all parties.

B. Cost per Hour Versus Years in Service

Figure II-1 depicts the maintenance cost history of all turbofan engines in airline operation. The points shown are for the JT3D engine chosen as a typical example since it entered service at the beginning of the airline jet era; and after twelve years, still accounts for a high percentage of the engine hours flown. The variation in yearly JT3D maintenance costs data was caused by various factors as discussed below.

The first and second years show the impact of early design problems. The greatest impact came from high engine oil sump heats which coupled with inadequate thermal stability of the lubricant, resulted in heavy maintenance activity and replacement parts costs.

The third year reflects the establishment of the maturing trend of the engine as a result of correction of early design problems, improved maintenance programs requiring less frequent removals for engine

reconditioning and more familiarity on the part of the flight and ground personnel in catering to engine requirements.

The fourth and fifth years show an anomaly from the maturing engine trend. Three significant factors were responsible. In the fourth year, severe erosion of the high pressure turbine (and to a lesser degree, the low pressure turbine) began to develop as a mounting problem. This impacted the fourth, fifth and to a limited degree the sixth year of service. The problem was identified as formation of hard carbon particles on the fuel nozzles which broke loose after building up to a critical depth and eroded the downstream turbine parts.

The heretofore unexperienced phenomenon was traced to elevated fuel temperature in the internal fuel manifolds because of deterioration of the fiberglass insulation - coupled with the catalytic effect of trace copper in Mexican refined fuel. The second and third factors affected the fifth year and carried through the sixth. They were the start of life limited parts replacement and installation of new design combustor components to extend parts lives.

In the middle of the sixth year, a revised maintenance program was instituted which further decreased the number of engines removed for restoration.

The seventh, eighth, ninth and tenth years reflect the combined effects of longer intervals between engine shop visits and refinements in all areas of engine management.

The eleventh year reflects a further maintenance program change to reduce to the absolute minimum the number of engines removed for restoration. This provides maximum opportunity to limit engine maintenance to that shown necessary by engine condition checks.

The twelfth year shows an upturn brought about by the effect of major engine case aging and the start of the second cycle of life limited parts replacement.

C. Fundamentals in Engine Maintenance Cost

The year to year variation in hourly maintenance costs is the end result of the number of engines removed from service for repair during a calendar year and the cost to repair the engine removed divided by the engine flight hours (EFH) flown during the year. The total number of engines removed is a function of engine reliability (maturity) and maintenance philosophy--overhaul or condition monitored maintenance. The cost per engine repair also varies with engine total operating hours and maintenance philosophy. Engine maintenance cost is the sum total of labor, material and outside service expended to repair engines removed from service for cause. The following sections address:

1. Maintenance Philosophy
2. Removal Rates vs. Time in Service
3. Cost of Engine Repairs vs. Time in Service
4. The Variation of Maintenance Cost Elements vs. Time
(Labor, Material and O.S.S.)

These sections will be followed by a discussion of the breakdown of the labor expended in a typical engine repair in section 5. Section 6 addresses the material consumed in engine repairs and major categories--expendables, repairables, life limited parts and rotatable components. A description of the type of repairs normally contracted to outside vendors is discussed in section 7, to provide an understanding of outside services (O.S.S.).

The last section(8) deals with cost accounting methods to provide an understanding of how cost data are accumulated.

1. Maintenance Program Philosophy and Cost Impacts

The airline's powerplant maintenance program is of extreme importance to safety of flight and day-in-day-out fleet operating reliability. Furthermore, it has a profound effect upon maintenance costs. In typical mature fleets, the powerplant maintenance costs average 48% of the total airplane maintenance costs. Because of its importance and cost impact, the powerplant maintenance program receives a high level of attention from the FAA (Federal Aviation Administration), the engine and power package manufacturers and the airline operators. The three interested groups, while acknowledging dedication to overall goals of safe, reliable and economic operation, assign different levels of importance to the various results of powerplant maintenance. Their first level concerns are as follows:

FAA - The principle aim of the FAA is to protect public safety in air travel. They do so by issuing regulations, approving maintenance programs and assuring compliance with these programs. Since safety is paramount and the FAA bears no direct accountability for economic consequences, the measures they initiate and enforce are frequently in the direction of increasing maintenance costs.

Manufacturers - The manufacturers' objective is to deliver a product and to support its operation at a reasonable profit. In accomplishing this, they must serve both of the other parties. Their product must meet the FAA's regulations and they act as the principal consultant to the FAA in safety matters, including maintenance related areas. They must also serve the airlines — their current and future customers. Hence, it

behooves them to give the airline all possible support in developing most economical maintenance programs. This is accomplished by assisting in the development of the initial program when the product enters service and supporting the airline in refining the program as maintenance experience builds up. Assistance is provided in identification of problems, design of improved parts, design of tooling, issuance of manuals/technical data and contribution of the combined experience of all customers.

Airlines - Airline survival is contingent upon supplying, at a profit, a service which the public will buy. It is the airline which must make the maintenance program work economically while meeting FAA requirements and by drawing support from the manufacturers as needed. To do this, the airline participates with the other two in establishing the initial program and refines it as he accumulates experience to make it more efficient and to adjust it to changing operating patterns or to cope with new mechanical problems. In the process, he calls upon the manufacturers for the inputs they can make and satisfies the FAA in matters which could affect safety.

In 1959, when the U.S. airlines began operating jet engines, they faced a maintenance challenge for which there was limited background. Military experience and early European operation were used as applicable, but principal reliance was placed upon airline piston engine programs which were familiar to the users and were well proven. The programs utilized at the beginning were called "overhaul" programs. They, like the piston engine programs, required that after the engine

had been operated up to a specified hour limit, it be totally disassembled and inspected. Parts were reconditioned in accordance with the maintenance manual, the engine was tested to demonstrate compliance with performance criteria and was then cleared for another specified time interval. The time between overhauls (TBO) was increased in increments of 200 hours after a specified sample of engines (usually six) were carefully inspected, measured and adjudged capable of reliable operation for the additional increment. As experience mounted and the engines demonstrated their safety and reliability potentials, TBO increase requirements were gradually made less stringent. First, the required sample quantity was decreased. Then the time increments were increased. Finally at the time when maintenance programs tailored to the turbine engine characteristics were being developed, the TBO programs had evolved to their ultimate stage. Operators who could meet the required FAA standards were permitted to specify their own sample sizes and increase increments. Early maintenance programs were costly because unnecessary work was performed at too frequent intervals while the true maintenance needs of the engines were being identified. As the sample quantities were reduced and the time increments increased, the maintenance costs attributable to the TBO programs naturally decreased.

The next generation of programs were variously termed scheduled shop visit (SSV), engine heavy maintenance (EHM) or modified TBO programs. This type program retained the feature of specified intervals at which the engine would receive substantial maintenance effort while making a further decrease in unnecessary work. As a prelude, all parts of the engine were reviewed on an average fleet condition basis for

problems, wear rates, demonstrated operating time capabilities and failure consequences. The maintenance program was then structured to bring the engine into the shop at specified intervals and perform prescribed maintenance on its parts. Typically an engine would be brought to the shop for combustor and turbine reconditioning. The compressor sections would be scheduled for a non-disassembly inspection only and if no damage was observed, no further work was required. At the next visit, (second SSV) the hot section and high pressure compressor would be reconditioned and the low pressure compressor again given a non-disassembly inspection. At the third SSV, the hot section and low compressor would be reconditioned and the high compressor inspected without disassembly. And so on. As experience was accumulated, the SSV intervals were increased and the work content refined — all in the interest of greater efficiency and lower maintenance costs. This phase resulted in lowering of maintenance program costs but still contained a significant drawback. Intervals and work content were tailored to the "weaker" engines and those in **better than average condition** were unnecessarily worked with consequent unwarranted maintenance costs.

The latest programs are known as condition monitored maintenance (CMM) or on condition (OC). Under this type program, there are no scheduled removals for reconditioning; however, removals are required as has always been the case for replacement of life limited parts. (These "opportunities" are utilized to incorporate design improvements, recondition parts as required and fix any problems exposed by the disassembly.) The engine condition is tracked through borescope inspections, oil analyses, performance parameter monitoring and visual

inspection for oil leaks, foreign object damage to the compressors or abnormalities viewed through the tailpipe. When symptoms of developing problems are detected in the individual engines, appropriate maintenance action is initiated. If performed with expertise, the engine is scheduled for correction at a time and place which will result in minimum damage to the engine, quickest and most economical correction of the problem and least loss of airplane readiness. This type of program reduces direct maintenance costs to the minimum since it initiates action only upon detection of problem symptoms. It does, however, increase indirect costs for instrumentation, diagnostic programs and management of large fleets of engines on an individual basis. Furthermore, it requires understanding and discipline throughout the maintenance department since there is a strong temptation to, "run it just a little longer" looking toward a more convenient time and place to take action.

Figure II-2 shows the history of various maintenance programs and the resultant rate for scheduled engine removals. (Total removals are the combination of scheduled and unscheduled removals.)

Most recent airline engines of the JT9, CF6 and RB.211 generation incorporate design features to complement the latest maintenance programs. Ports have been added at strategic locations for borescope insertion. (Incidentally, borescopes have been developed to a high degree. They carry their own intense cool light sources and provide not only internal engine mobility and accurate viewing, but also adapters for film and TV cameras.) The engines are readily separable into modules so only the discrepant area needs to be worked. Ready spare modules can be added to an engine during repair with a high level

of assurance that they will meet dimensional, vibration and performance specifications. Provisions are available for insertion of radio isotope pellets to facilitate non-disassembly structural inspections and some engines can be equipped with internal accelerometers adjacent to the main bearings for sophisticated vibration monitoring.

More and more, the QEC's are being designed for optimum access to the engine mounted accessories, the thrust reverser, and the engine exterior surfaces, plumbing, wiring and brackets. Hard points are incorporated in the airplane structure for installation of hoists and support rails to facilitate powerplant changes and "on the wing" engine module exchanges. All of these features are exploited to the fullest in current powerplant maintenance programs with corresponding cost benefits.

In comparison to the original jet engine maintenance programs which required total disassembly of six sample engines in order to substantiate a TBO increase of 200 hours, current new engine maintenance programs apply effort more efficiently. Specific engine parts which are identified by development test experience are singled out for critical monitoring. This may take the form of borescope or isotope inspections with specified time/cycle limits. Where this cannot be done, full advantage is taken of "opportunity inspections"—instances where the engine is partially disassembled for other reasons and the critical part can be inspected without further disassembly. Only in situations wherein there has been no prior opportunity to inspect the critical part is disassembly mandatory. Inspection findings are reviewed by the FAA, manufacturer and airline and compared to the accumulated industry experience up to that point. In this way engine condition trends are utilized to the fullest to

allow the new engine to be put on a CMM maintenance program at the earliest possible time. Typically current maintenance programs for new powerplants avoid the necessity for complete engine disassembly as a requirement for substantiating operation on a CMM program.

2. General Trend of Total Removal Rates Vs. Time

When a new model powerplant enters airline service, it has accrued a limited amount of operation. Engine manufacturer's development and FAA certification testing have been conducted and the airplane company has accumulated additional operation during powerplant ground rig testing, development flight testing and airplane certification testing. Ground running is made as realistic as possible by utilizing flight components and accessories as they become available and by simulating typical flight profiles; i.e., start, taxi, takeoff, climb, cruise, descent, landing, reversal, shutdown and cool down. Problems revealed by this running are analyzed by the manufacturers and decisions are made either to treat the problems as isolated occurrences or to withhold action for better definition of the causes or to initiate design revisions. Engines are delivered to the airplane company six to nine months prior to installation in the new airplanes and hence airlines receiving early delivery airplanes must cope with these problems. Correction prior to delivery is usually limited to flight safety items since this is an expensive course of action and it can jeopardize airplane delivery schedules.

Figure II-3 depicts a typical relationship between removals for all causes and time in airline service for turbine powerplants. The higher removal rates in the early years of operation result from a number of factors associated with adapting a complex, new mechanism

to its routine working environment. Typical removal factors for roughly the first three to five years are as follows:

- a) Design deficiencies (revealed by predelivery testing) causing random failures.
- b) Conservatism by the airline in diagnosing trouble symptoms of unfamiliar mechanisms.
- c) Real or suspected damage caused by operation of unfamiliar equipment by flight and ground crews.
- d) Disassembly for inspection of critical powerplant parts to check for potential problems or growth of known problems.
- e) Parts damage or assembly errors occurring in the shop or on the line due to handling unfamiliar mechanisms.
- f) Incorporation of unsuspected, sub-standard parts resulting from "growing pains" in the spin up of the manufacturing processes.
- g) Incorporation of new design parts to correct high impact problems.
- h) Correction of design deficiencies manifested after longer term operation.

As these and similar problems are gradually brought under control, the powerplant settles into a maturing phase characterized by decreasing removal rates and gradual flattening of the curve at its lowest level. The powerplants are capable of running longer; fewer mistakes are made in operation, maintenance and problem diagnosis; and the airline develops techniques to manage the required maintenance in patterns which minimize removals.

In the latter years of operation, the rates tend to rise because of aging effects of major, long life, structural parts. Parts which have

experienced thousands of stress cycles and have undergone successive repairs and heat treatments will not run as long between repairs as relatively newer parts. Also, there is a tendency, as fleet retirement date weighs more heavily in the decisions, to deliberately build "short time" engines in order to extract remaining life from the accumulated parts rather than invest large sums in new parts which will be used only a fraction of their lives.

3. Cost of Repairs vs. Years in Service

Figure II-4 illustrates the time trend of the unit cost for shop processing of a typical airline powerplant. Processing consists of repair, replacement of life limited parts and/or parts reconditioning. It is noteworthy that although the trend over the twelve year period is continually upward, the slope decreases steadily as the engine matures.

In the early years, the cost per repair is at the lower levels. Engine processing concentrates on fixing specific problems involving labor and replacement of inadequate parts. At this time there is no requirement for broad scale reconditioning.

During the intermediate years, the average cost per repair is a composite of the effects of a number of factors, some mutually offsetting and other having discrete effects. Typical of these are the following:

FACTORS INCREASING UNIT COSTS

- a) Cost of new design parts to fix early development problems.

FACTORS DECREASING UNIT COSTS

- a) More familiarity, less conservatism equating to less unnecessary maintenance action.

FACTORS
INCREASING UNIT COSTS

- b) Damage due to new problems revealed by longer running times.
- c) Groping for understanding of new problems, meanwhile experiencing undue damage to associated parts.
- d) Cost of improved designs for higher reliability and/or parts lives.
- e) Life limited parts replacement.
- f) Accumulated parts times/cycles.

FACTORS
DECREASING UNIT COSTS

- b) More familiarity, less unwitting operating/handling damage to parts and engines.
- c) Better diagnosis and troubleshooting minimizing damage to associated parts.
- d) Improved reliability/lives of replacement parts.
- e) Longer lives of later design life limited parts.
- f) Increased skill in all phases of operations and maintenance management.

The net effect of the interaction of the various factors is to flatten the rate of increase of unit processing costs with time. In the case of the engine experience illustrated by Figure II-4, an unusually wide deviation from the norm occurred at the eighth year. For the first six years, only a very small percentage of the engines in the fleet had been reconditioned. Allowable time between overhauls had been steadily increased guided by disassembly and inspection of a limited number of sample engines as the means of establishing the engine's reconditioning requirements. At the 6.5 year point, a new maintenance program was instituted which required specific reconditioning activity at specified elapsed times since last similar activity. The effect of this change is shown by the fact that in the eighth year there was a 59% increase in the manhours expended per engine over that expended in the sixth year. Since it required 24 months for a routine cycle of the engine fleet through the shop, the increased unit costs reflected the last half of the seventh year, the full eighth year and the first half of the ninth year. The benefits of

the program show up in the tenth and subsequent years.

The latter years reflect the most efficient management of the power plants exerting an influence toward decreasing unit costs. However, parts aging effects require increased maintenance labor for parts reconditioning; or alternatively, increased out-of-pocket costs for new parts. It is likely that an increase in slope will occur beyond the end point shown on the curve because of the second cycle replacement of life limited parts and the retirement of worn out major structural engine cases.

4. Maintenance Cost Elements versus Time

Figure II-5 exhibits what is considered a normal distribution in relationship between the labor, material and outside services elements. Warranty credits are of much greater significance in the early years of operation and then are reduced substantially as the engine matures. As demonstrated, there is an occasional excursion in the warranty credits due to problems that arise and are accepted as the responsibility of the manufacturer concerned. In Figure II-5, the excursion away from the normal at the sixth and seventh year of operation was as a result of problems in the engine fuel systems which caused extensive secondary damage to the hot section components. As the fuel system problems resulted from design and manufacturing deficiencies plus a fuel supplier quality control deficiency, substantial claims were acknowledged. The cyclic effect on material costs as a result of major hardware replacement (life limited parts, etc.) is also apparent. It has been noted with the newer high bypass engines, that the percentage of the labor, material and OSS elements in total maintenance

cost are different. There appears to be a higher percentage of total cost spent on material and OSS with lesser percentage spent on labor. It is anticipated, however, for the mature engine only modest differences will occur. The latter sections of this report deal with this area in detail.

5. Engine Maintenance Labor Elements in Engine Repair

Figure II-6 depicts the breakdown of the major labor costs elements arising from the removal of a CF6-6 engine in service, transportation to the engine maintenance facility, processing through the facility and return for re-installation on the aircraft.

The major labor cost elements arises at the engine maintenance facility. The labor expended at the maintenance facility constitutes 87% of the total labor expended in engine repair. The balance, (13%) is expended in installation, removal and transportation. Certain other differences become apparent also, and are explained as follows:

a) Engine Removal (3%) versus Engine Re-Installation (2.5%)

Although the engine re-installation labor element includes that necessary to rig controls, leak check the various systems and perform an engine ground run, these facets are not enough to offset the labor expended to install tooling necessary to facilitate access for engine removal and any corrective action generated by inspection of the cowls, associated hardware and pylon mounted airframe/powerplant related systems and components.

b) QEC Strip (1.2%) versus QEC Build-Up (1.6%)

It is easier to remove QEC hardware than re-install same. The reason for this arises from the need, during installation, to

insure equipment alignment, fits and clearances, cable routings, etc., are properly achieved. This precludes problems occurring in subsequent engine service due to interference, chafing, and over stretching of electrical cables, brackets, etc.

c) Split Engine Into Modules (3.8%) versus Joining Modules (7.6%)

Again, the requirement to inspect, measure and insure correct alignment, fits and clearances, retaining nut torques, etc., causes the build process to be more lengthy than disassembly. Only in special circumstances, i.e., sample engine, failure investigation, or similar programs, is it necessary for the alignment, fit, clearances, torque values of certain components to be measured and recorded during engine disassembly.

6. Engine Maintenance — Material Consumption

Material consumed during the operation, maintenance and repair of propulsion systems falls into three basic categories. These are: EXPENDABLE, REPAIRABLE, and LIFE LIMITED PARTS. There is a fourth type of material, namely ROTABLES, which is the term given to a component or removable subcomponents of an engine or accessory usually capable of replacement when the engine is installed in an aircraft. Rotables, however, also consist of the three basic categories and, therefore, need not be treated separately. Each of the categories are defined as follows:

a) Expendable Parts

Items for which no authorized repair procedure exists and whose cost of repair would normally exceed that of replacement. These are further categorized into the following groupings for control

purposes:

- Mandatory (100%) Replacement Items - Those required to be discarded and replaced at each disassembly in keeping with overhaul specifications and/or procedures. Examples: Packings, seals, gaskets, back-up rings, diaphragms, cotter pins, etc. Shop requirements are forecast using assembly production rates, quantity of article per NHA (next higher assembly) with an added allowance for loss, damage, inspection, rejection, etc.
- On Condition Replacement Items - Includes both integral and non-integral piece parts of assemblies that are reused or replaced based on inspection findings. Some reclamation is possible through simple refurbishment or adjustment processes. Examples of integral items are: dowels, pins, studs, inserts, bushings, sleeves, guides, etc. Examples of non-integral items are: bearings, races, springs, covers, orifices, housings, hoses, wire, bulbs, brackets, etc.
- Hardware Items - Includes bolts, nuts, washers, screws, and other fastening devices removed or disturbed during assembly overhaul or maintenance. Actual usage is a product of volume. True attrition is a function of amounts non-reclaimable through simple refurbishment processes, i.e., cleaning, sorting, identification, packaging, etc. Reclamation may be performed by the airline internally or through routing to outside agencies specializing in this function.
- Bulk Material - Includes materials of liquid, paste, bulk, cloth, plastic, or comparable composition used in random quantity

during overhaul or maintenance processes. Examples are: oil, chemicals, paints, cleaners, solvents, abrasives, metals, fabrics, etc.

b) Repairable Parts

These are detailed or non-detailed assemblies which, by means of an authorized repair or recovery procedure, may be continually returned to a fully serviceable condition, provided economic factors justify their repair in lieu of replacement.

c) Life Limited Parts

Certain components within turbine engines are life limited on an hour or cycle basis regardless of condition. These are primarily rotating components and consist mainly of rotor discs. Such life limits are established and continually verified to preclude rupture of the rotor discs which could cause an unacceptable risk to the airplane occupants in addition to persons on the ground.

In the case of rotating components, the governing factor is usually cyclic history. This cyclic history must be kept in two forms, viz, the total number of cycles operated and the number of cycles remaining to achieve the life limit.

Each of the following are considered as one cycle:

- 1/ A typical flight consisting of start, take-off, landing and shutdown.
- 2/ An airstart/engine shutdown and start during flight.

3/ A "touch and go" landing.

NOTE: Item 1/ applies to all flight; Items 2/ and 3/ apply to pilot training flights only.

Where the life limiting parameter is hours, this is normally measured in flight hours, i.e., the time period between wheels off during take-off and wheels on during landing. Engine hours, therefore, become a multiple of aircraft flight hours in relation to the number of engines installed.

Again, operating time history is retained in two forms, viz, total time accrued since new or time since last installed (as determined by the controlling parameter) hours operated and the number of hours remaining. Total time accrued is the summation of the number of installed hours achieved.

7. Engine Maintenance — Outside Service

Outside service, i.e., the use of non-airline owned off-site facilities, are used to supplement and complement the machine tools and processing facilities usually owned and operated by the airline.

These outside service facilities are utilized to avoid the expensive investment in short term use equipment, such as that necessary for special or highly complex machining operations; specialized repair or refurbishment processes, e.g., "D" (detonation) gun application of Tungsten Carbide; Ni-gold (nickel-gold) furnace brazing, etc., of components; and peak demands occasioned by campaign type modifications and repairs which have caused the in-house facilities to be load saturated.

When economics (dollar volume) justify, consideration is then given to expanding the in-house capability through capital investment in additional tooling and facilities. Examples of equipment purchases to perform in-house repair of engine components that were previously subcontracted to outside vendors are:

- a) Electron Beam Welding Machine
- b) Electrostatic Discharge Milling Machine
- c) Flame Spray Equipment
- d) Vacuum Furnaces
- e) Digital Controlled Milling Machines
- f) Engine Fuel System Component Test Stands

As many engine hot section components are coated with proprietary materials through a proprietary process, it is required that such be returned to the manufacturer for refurbishment and/or repair.

Again, when economics justify, licenses to perform such repair/refurbishment processes in-house are sought from the manufacturer, e.g., "Codep" coating of CF6 engine high pressure turbine blades and nozzle guide vanes; Jo-coating of Pratt & Whitney engine turbine components.

Experience has shown that engine maintenance material costs are usually reduced by such in-house activity as the investment in material to maintain the pipeline to the vendor's facility and the vendor's facility charges are eliminated.

There are instances, however, where the vendor because of his volume from the total industry and expertise in the repair/refurbishment procedure, is able to perform a service at a cost much lower than the airline would be able to perform that service in-house.

Increasing labor costs in the airline industry, coupled with a better awareness of the potential repair market of many products by more enlightened manufacturers, has caused this latter situation to increase. For example, it is currently more economic to send compressor and turbine stator vanes, turbine blades, stationary air and oil seals, to specialized vendors and manufacturers for vane and platform replacement; special repairs, modifications and coating; honecomb replacement and knife edge respectively than perform the work in-house.

Figure II-7 exhibits the Outside Services costs in relation to the introduction in-house of each engine model.

The excursion during 1964 and 1965 was caused by a decision to utilize a local vendor for the repair and flame spray of JT3 burner cans due to in-house capacity restrictions. Again, in 1972, an excursion is apparent and this results from receipt of approval for repairs to JT3 and JT8 nozzle guide vanes by vane replacement and JT8 compressor stators by vane and platform replacement by specific vendors.

Figure II-8 displays the cumulative capital investment for machine tools, special process equipment, jigs, fixtures and facility expansion, etc., to cater for the introduction in-house of additional engine types and the increasing need of further repair capabilities.

The rapid escalation in capital investment during 1971 and 1972 was brought about by the equipment necessary to handle the CF6 and ultimately the JT9 engine. Many of the then current machine tools, etc. were incapable of handling the larger diameter components of these engines such as the fan frame and fan case assemblies.

It is anticipated that investment in facilities will be stabilized until the next engine type is introduced. However, investment in repair tooling, processing equipment, etc., will continue at about the same rate as previously as more repair capability becomes economically feasible.

8. Airline Cost Accounting Methods

To facilitate the collation of labor, material and repair service charges related to the processing of an engine through the facility, an accounting system has been developed.

First, the engine is assigned a Work Order and all charges made against the engine are collated under this number.

The engine is further broken down into serialized modules and these numbers are also used to collate the charges developed by work on them.

Finally, each work process has a shop work order card either computerized or manually written. Each card has a number and charges are collected by operation number or line on the card.

Each shop is also provided with a charge code in order that an awareness for which area the expense is being or has been generated is retained.

All labor, material, in-house repair and outside service charges are collected and retained independently under the various shop work order numbers and charged against the engine work order numbers.

Items forwarded to outside vendors for repair are processed under a repair order number and charges accrued in the outside services ledger

against each particular engine or module.

Computerized accounting methods have assisted enormously in acquiring, retaining and distributing this data in various formats in order that either management or a particular user can be aware of major expense items and initiate corrective action programs as necessary.

In collating charges against a given engine or module, the labor expense element is charged as it occurs. The expendable material is usually issued in bulk to the shop and charged against the shop at that point. Charges for expendable material, therefore, can only be averaged against the number of engines/modules/submodules processed versus the dollar value of the expendable material issued to the shop.

Repairable items are charged with the repairs performed, and, in the event that the part reaches a point where it is no longer economically repairable, it is then scrapped and the charge registered against the engine/module on which it has last been installed.

The basic problem in the current accounting method is that the engine labor, material, and outside service charges are collected during the year and measured against the engine hours currently being flown rather than the hours that each repaired engine has flown.

While over a long period this has a somewhat averaging out effect, it can be very misleading, particularly during the introduction or expansion of an aircraft fleet.

Newer engines of a given model usually incorporate latest improvements and generally operate for longer periods than their predecessors.

This has an effect of diluting the real engine operating cost until all engines have matured. It is possible for an airline to lower the maintenance cost of a given engine during a specific period just by increasing the size of its fleet with new or newer aircraft. Therefore, to assess the effects of an improvement, one must always be aware of the fleet size during the period under review, otherwise a false impression of improvement could be gained.

The foregoing are some of the factors that influence maintenance costs over a specific period of time and suggest caution be used when reviewing cost data; otherwise, improper conclusions could be drawn.

**TOTAL MAINTENANCE COST PER ENGINE FLIGHT HOUR
VS. TIME**

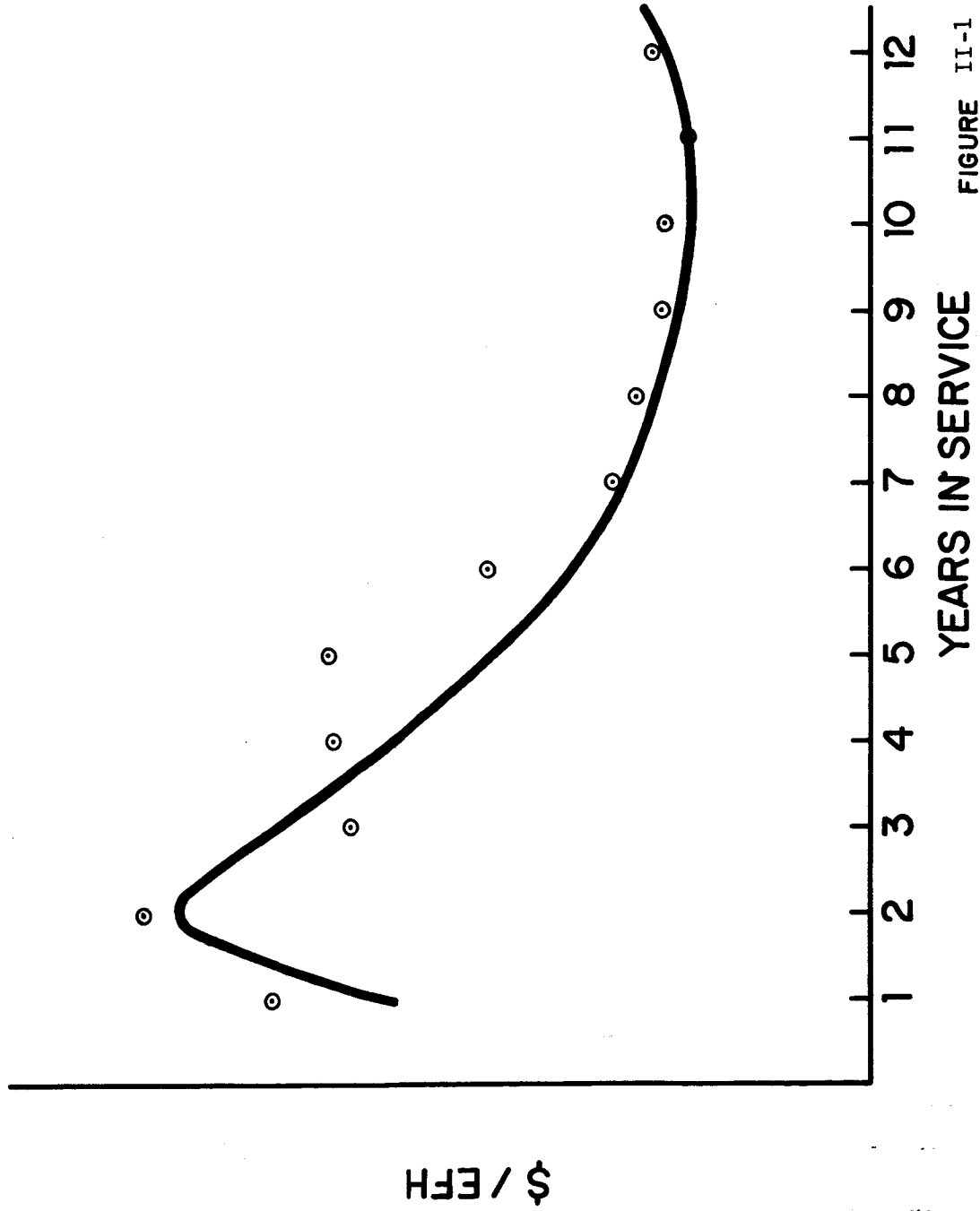


FIGURE II-1

MAINTENANCE PROGRAM ENGINE REMOVAL RATE VS. TIME

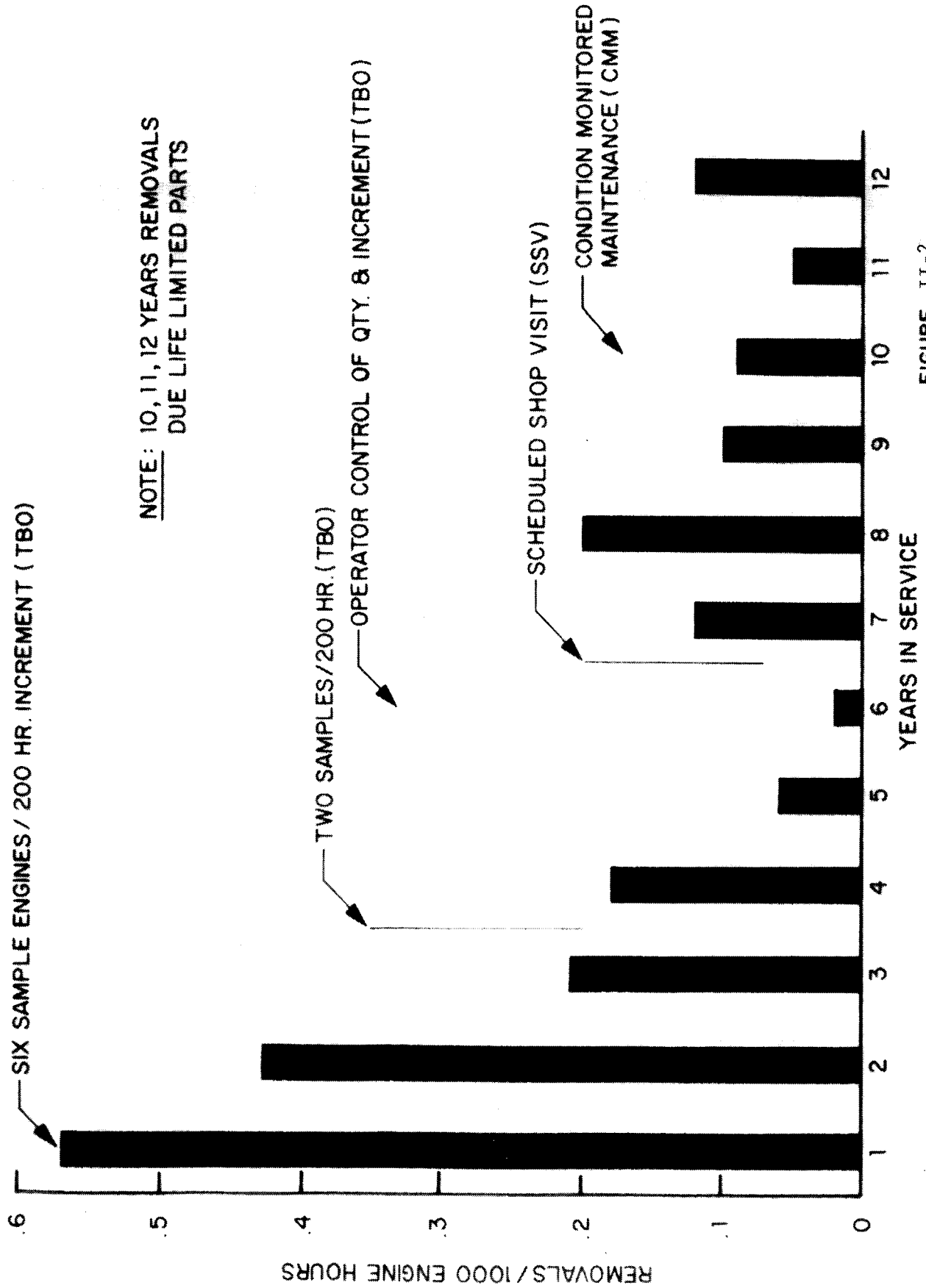


FIGURE II-2

ENGINE REMOVAL RATES VS. TIME [FOR OVERHAUL AND REPAIR]

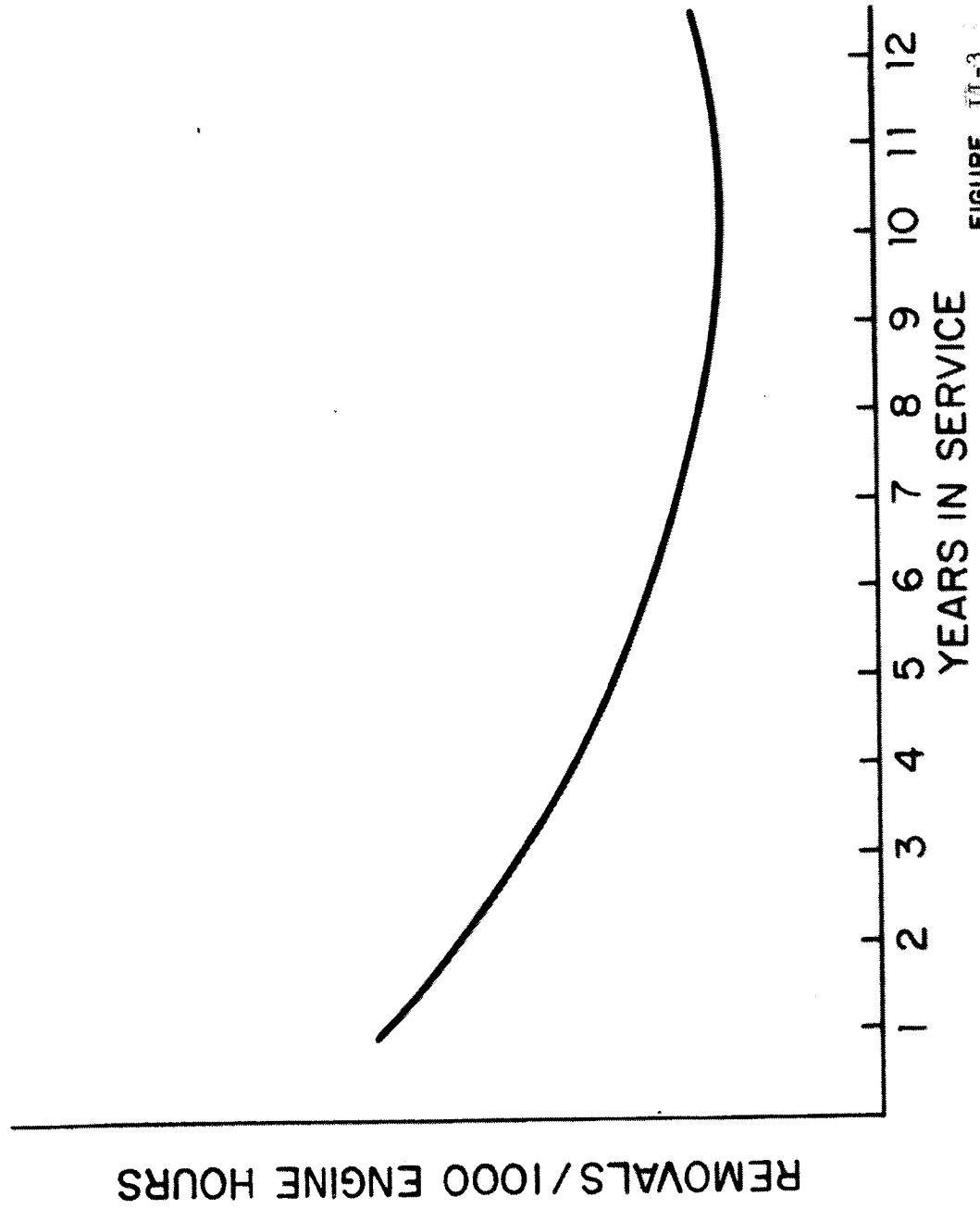


FIGURE II-3

TOTAL MAINTENANCE COST PER REPAIR vs TIME

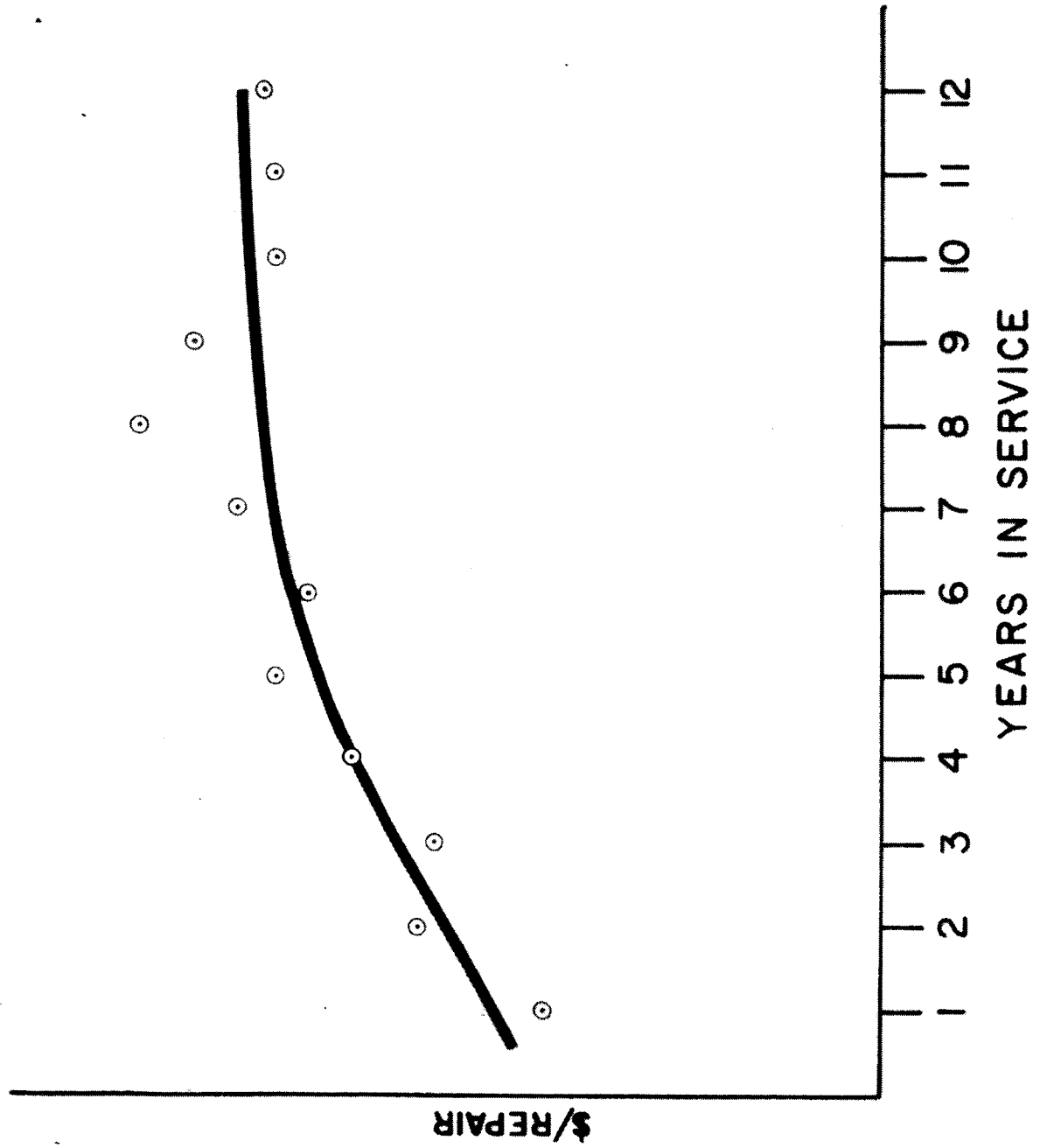
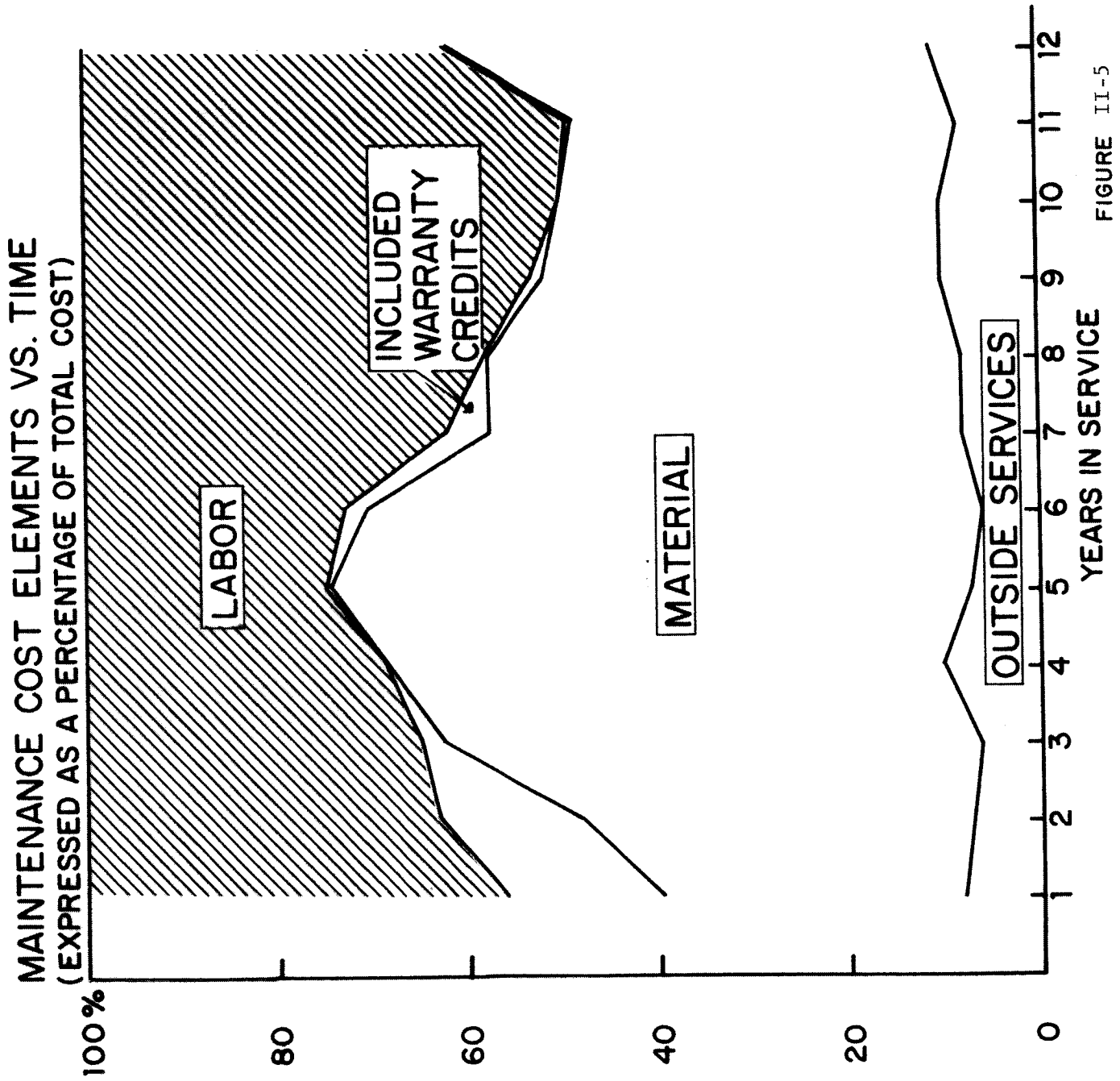


Figure 11-4



ENGINE REMOVAL CYCLE LABOR ELEMENTS

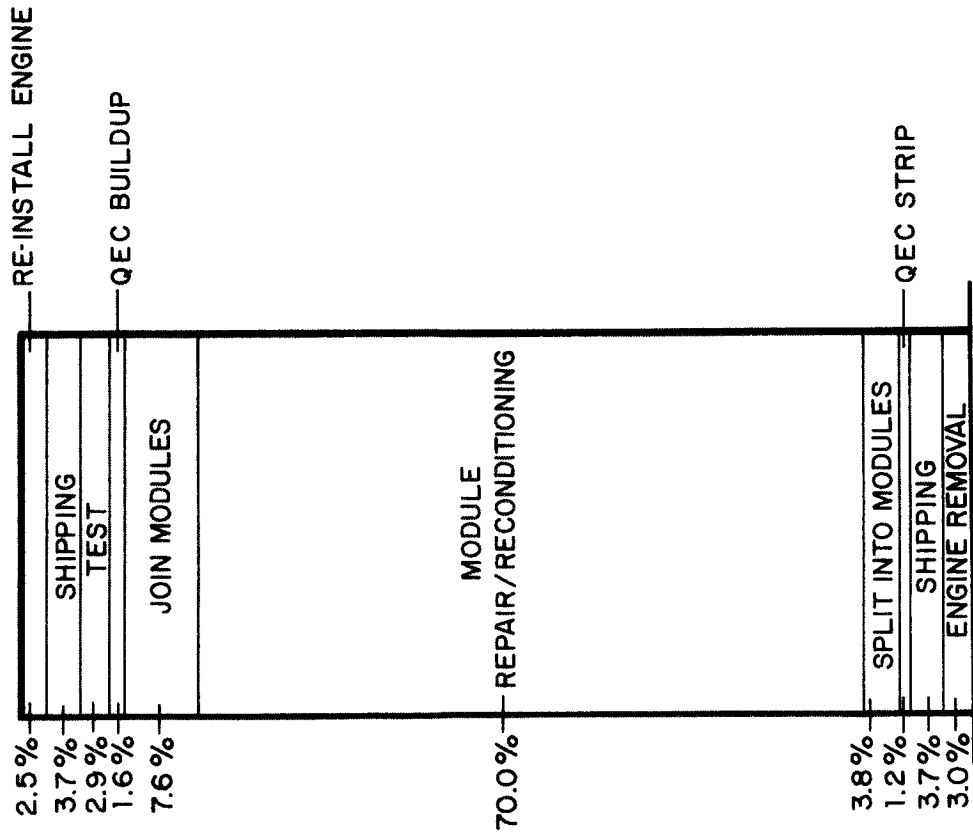


FIGURE II-6

OUTSIDE SERVICES COSTS
(EXCLUDES JT8 & JT9 COSTS AT OUTSIDE REPAIR AGENCIES)

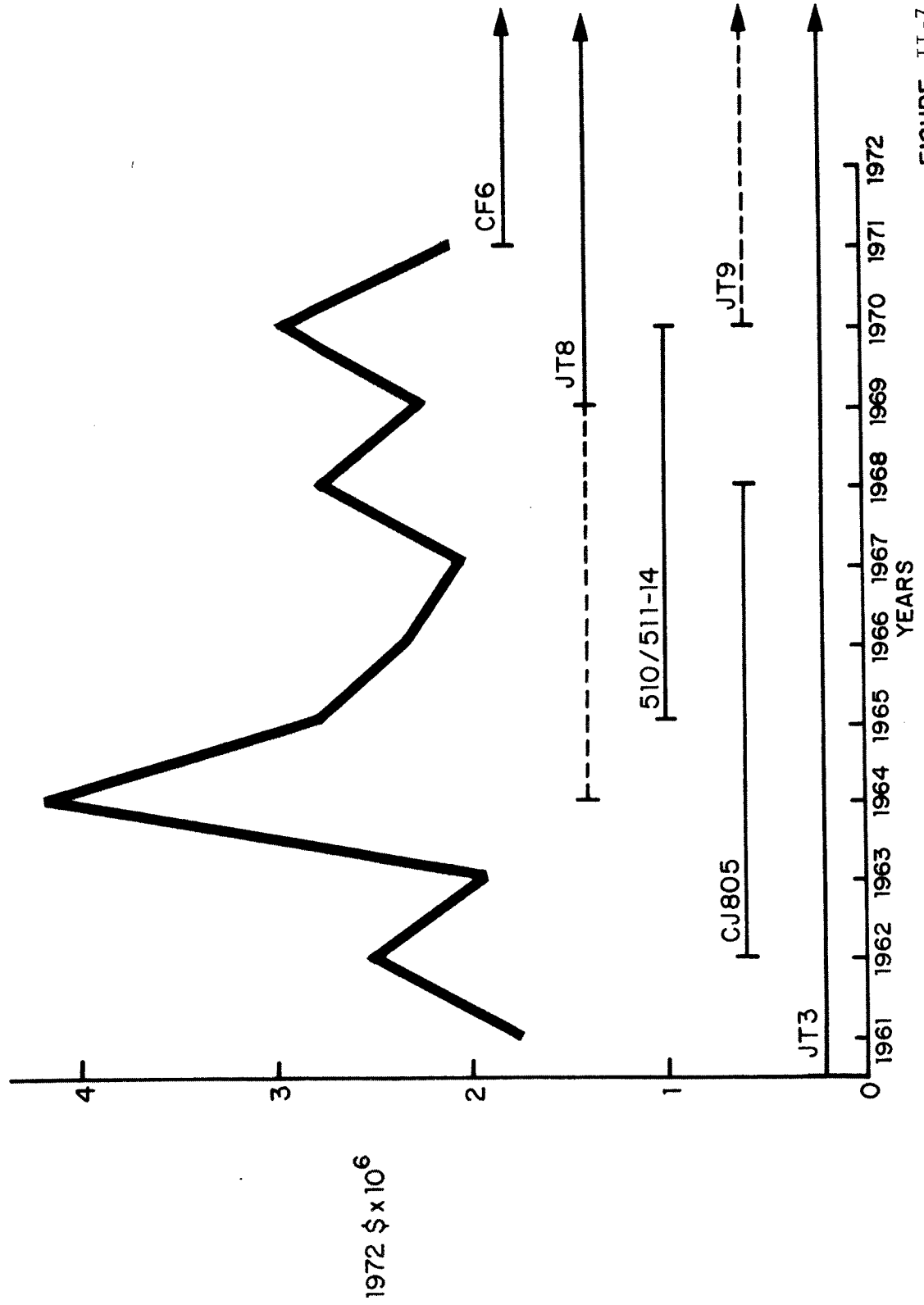


FIGURE 11-7

CUMMULATIVE CAPITAL INVESTMENT IN TOOLING & FACILITIES

(EXCLUDES JT8 & JT9 INVESTMENT AT OUTSIDE
REPAIR AGENCY)

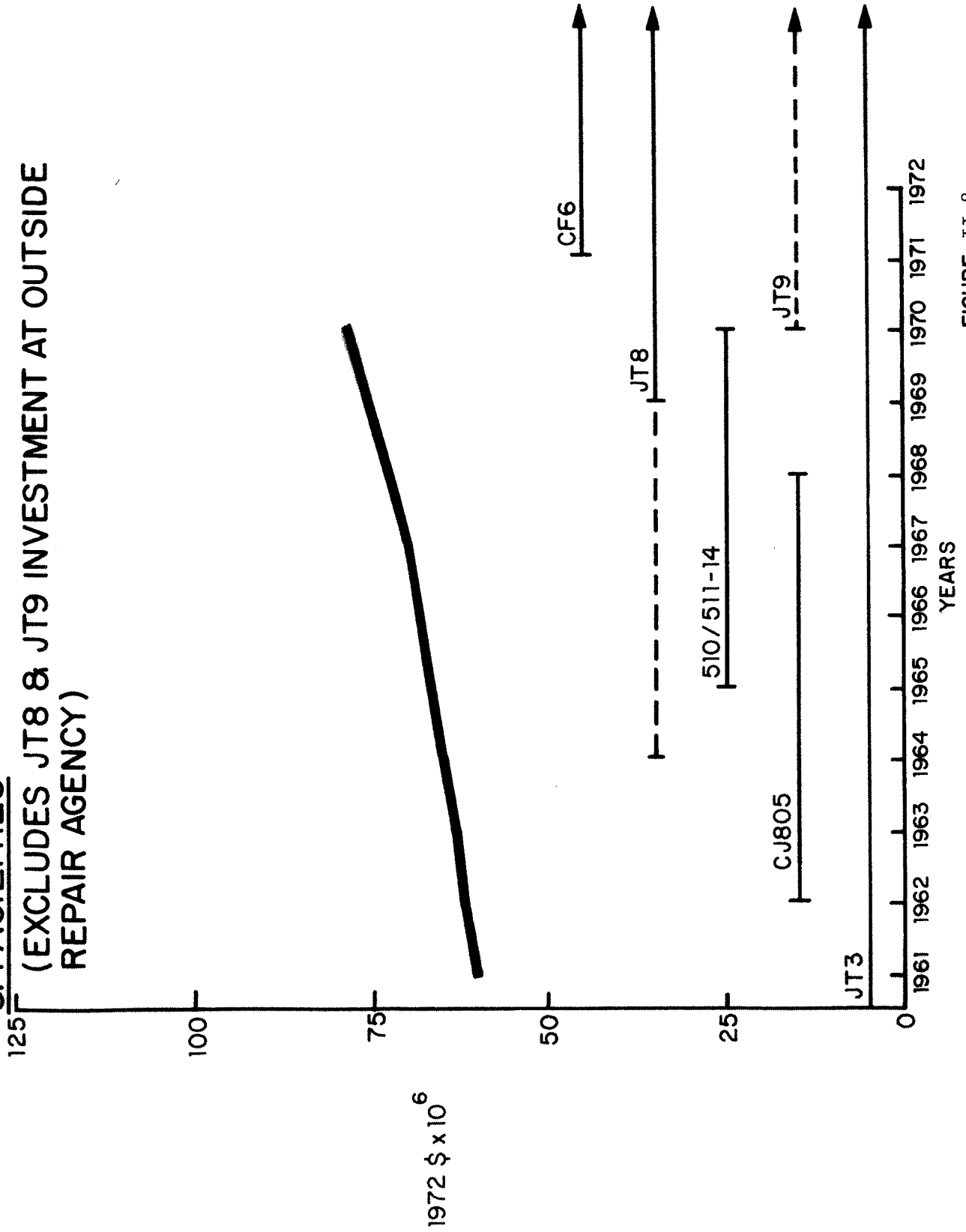


FIGURE II-8

III. DATA ANALYSIS AND TRENDS

A. Introduction

The first step in the analysis of total power plant maintenance cost is to separate the maintenance required by the installation components from that required by the basic engine. Figure III-1 depicts the historical trend of total power plant maintenance cost for the P&WATM JT3D, JT8D and JT9D-3A (referred to as the JT9D) engines. Except where stated, all maintenance cost data is from American Airlines CAB Form 41. Figure III-2 presents a breakdown of the maintenance costs of the power plants studied. The analysis of trends and data will begin with the basic engine (Sections B, C and D), followed by the analysis of the installation components. Outside services are ultimately dependent upon airline "make or buy" decision criteria. As shown in Figure III-2, outside services represent only a small part of the total maintenance cost picture (approximately 6%) and were therefore excluded from detailed analysis. All costs are expressed in 1972 dollars to correct for inflation.

General Electric CF6-6D data points are shown on a number of the plots which follow. These data were included to broaden the perspective by including an additional high bypass engine - made by another manufacturer. No data is shown for the first calendar year in service since flight hours were minimal and no engines were repaired. Second and third year data are heavily influenced by typical early experience as previously discussed. Figure III-2

reflects this situation inasmuch as Outside services represents 22% of maintenance costs. During this "initial experience", many repairs were accomplished by outside sources having specialized facilities and tooling. These functions will be brought "in-house" or continued by outside contract as further experience provides guidance for most cost effective handling. Discussion of the CF6-6D data was not included in the text because of the "early service" status of the engine.

B. Basic Engine Total Maintenance Cost and Trends

Engine maintenance cost is typically expressed in terms of dollars per engine flight hours. Although this term is convenient for many uses, it has shortcomings when comparisons are made between engines of different sizes, experience levels, technology, and characteristic duty cycles. An analysis of maintenance cost must consider the elements of dollars per hour:

$$\text{Dollars/Hour} = \text{Dollars/Removal} \times \text{Removals/Hour}$$

In order to normalize for engine size (and hence cost) effects, maintenance cost/engine price trends are presented. All of these are for each engine's characteristics flight length. The effect of flight length on engine removal rate is shown to complete the normalization.

Figure III-3 shows total basic engine maintenance cost per hour since time of introduction for the three study engines. The trend toward lower maintenance costs as an engine matures and as its introductory problems are corrected with a continuing development program is quite evident in the JT3D and JT8D data. The JT9D has not been in service long enough to reach its mature level. It is expected that engineering changes being incorporated into the JT9D-3A will soon result in reduced maintenance costs as shown in Figure III-3. Figure III-4 adjusts the trends in Figure III-3 for engine price. Of interest in Figure III-4 is the relative position of the much larger JT9D when maintenance cost is adjusted for engine price.

Figure III-5 presents total basic engine maintenance cost per repair since introduction. Figure III-6 shows the historical cost per repair normalized to engine price. Cost per repair tends to increase to a mature level, where it remains relatively constant. This is due in part to a corresponding increase in average engine age coupled with an increasing time between shop visits (decreasing removal rate).

The reduction in maintenance cost on a dollars per hour basis with maturity is due to the trend shown in Figure III-7 which shows the total engine removal rate since time of introduction. Removals include all scheduled and unscheduled removals - convenience removals were excluded.

The engine removal rate starts out at a high level and decreases to a mature level approximately 5 to 8 years from introduction. The average rate for the JT3D during its first five years of service was approximately 3.2 times the mature value while the JT8D was 2.3 times its mature value.

It should be noted, however, that the JT3D and JT8D engines were operating under a fixed Time Between Overhaul concept during their initial years of operation rather than the Condition Monitoring Maintenance philosophy currently used by many airlines. The high engine removal rate in the early years of the JT3D and JT8D was partly due to the different maintenance philosophy. If the removal rates were adjusted to remove a portion of the early scheduled removals, then the factors between early to mature experience for the JT3D and JT8D are 2.5 and 2.0 respectively. The JT9D has not been in service long enough to reach its mature rate, but projections based on incorporation of engineering changes also show a reduction in removal rate as shown in Figure III-7.

Engine removal rate is greatly affected by average flight length. Figure III-8 shows the typical relationship between flight length and the mean time between removal for a mature engine based on industry experience. Longer flight times yield a fewer number of cycles per hour and hence a lower number of removals per hour. For example, an engine with 1.25 hour flight length and a known mean time between removal would have a new mean time between removal of 1.3 times the known level at a 2.5 hour flight length.

C. Engine Maintenance Labor Cost

Maintenance labor cost when expressed in dollars can be presented in many different ways resulting in radically different answers. Labor costs can be presented for direct labor only or for fully allocated labor which includes overhead and maintenance burden and may be as much as three times the direct labor alone. When engines are repaired outside the airline's shop, the vendor will apply his own labor rate which may not be the same as that of the airline. The vendor's rate may include the aforementioned overhead, burden, and also handling charges and profits. Another problem with using maintenance labor

dollars is that the labor rates increase each year. To compare properly one year's experience with another and one airline's experience with another, all the costs must be adjusted to a constant labor rate. To avoid the confusion that might occur with maintenance labor dollars, the maintenance labor cost analysis presented below has been performed on a direct maintenance man-hour basis. To convert these manhours to dollars, it is simply necessary to multiply by the appropriate labor rate.

1. Maintenance Labor Cost for Complete Engine

Maintenance labor cost is made up of two categories - line and shop maintenance. Line maintenance as the name implies, is performed on the flight line or in the hangar with the engine installed in the aircraft. Shop maintenance is performed in the airline's maintenance shop after the engine is removed from the aircraft. Shop maintenance accounts for approximately 80-85% of the maintenance labor cost.

Figure III-9 shows line and shop manhours per engine flight hour (MH/EFH) for the JT3D, JT8D and JT9D engines since start of service. This plot shows that the maintenance labor per engine flight hour decreases substantially as an engine matures. This is due to a substantial reduction in the engine removal rate with time (Figure III-7) due to product improvement programs to eliminate initial problems plus changes in maintenance philosophy to assure maximum utilization of the engine. The JT3D currently has the lowest MH/EFH but when compared at the same years of service point the engines are all very close together. It is anticipated that the JT9D engine will follow the same pattern as the 3D and 8D engines and its mature MH/EFH will also approach 0.60.

Since shop maintenance represents the major portion of the total labor

cost, only this portion has been analyzed in detail, and the following discussion will include only shop labor. Figure III-9A presents the man-hour per engine flight hour trend for shop maintenance only.

Figure III-10 illustrates the manhours per engine flight hour trend when normalized by engine price. The JT9D is substantially lower than either the JT3D or JT8D. It is expected that the 9D will remain lower than the 3D and 8D since, as explained previously, the unadjusted manhour per flight hour for the 9D is expected to approach the 3D and 8D values.

The manhours per repair, shown in Figure III-11 as a function of years of service, increases with time to its mature level. This is not surprising, however, since it is reasonable to expect more repair manhours to be required as the engine parts accumulate a large number of flight hours. The JT3D first five year average is only 70% of its mature value while the JT8D first five year average is 90% of its mature value. Although the manhours per repair for the JT9D are somewhat less than the JT3D and 8D currently, the 9D manhours appear to be still on the rise. Due to the modular concept incorporated into the JT9D, which lowers the manhours per repair, it is expected that the mature JT9D manhour values will be no higher than the 3D and 8D values though it is a much larger engine with significantly higher thrust.

Manhours per repair, normalized for engine price, versus years of service is shown in Figure III-12. This plot shows the JT9D at a much lower rate than the 3D and 8D. It is expected that the JT9D on this basis will remain substantially below the JT3D and 8D since, as stated previously, it is not unreasonable to expect the actual JT9D manhours per repair to be approximately the same as the 3D and 8D.

2. Breakdown of Labor Cost by Module

To determine the relative contribution of the various sections of the engine to the total labor cost, detailed American Airlines records for 1968-72 were analyzed for the JT3D; 1969-72 for the JT8D and 1972-73 (January-June) for the JT9D. Figure III-13 shows the average manhours per engine flight hour for each of the three engines, broken down by engine section for the time period analyzed. A predicted mature JT9D estimate is also provided. Figure III-14 shows the relative contribution of each section as a percent of the total manhours per engine flight hour. The three highest contributors for the JT3D are the low turbine, diffuser, and engine accessory sections while the three highest for the 8D are the high compressor, diffuser, and miscellaneous basic engine. The highest contributors for the JT9D actual experience to date are the high turbine, the high compressor and the engine accessories. For the mature JT9D, however, the predicted high manhour consumers are the high compressor, the high turbine and the combustor. Figures III-15, 16 and 17 present cross-sections of the three engines, cross-hatched to illustrate the various sections of the engine.

Maintenance manhours per engine flight hour are made up of two elements - the manhours per repair and the frequency of repairs. To properly analyze the difference in manhours per flight hour for the modules, each of the parameters must be analyzed separately. Due to time limitations, only six of the thirteen modules were analyzed in detail. These six modules are the major contributors, however, and represent 67% of the JT9D shop manhours per flight hour.

a. Manhours Per Repair

In analyzing the manhours per repair, an effort was made to determine how the different manhours per repair related to module size, com-

plexity, and technology employed. It was felt that correlation between these factors, or some combination thereof, would identify the reasons for the differences and provide an analytical tool on which to base predictions for advanced engine designs planned for future commercial use. While the manhours per repair correlating parameters selected for each module should not be considered unique or optimized due to the limited data available, they are considered reasonable for the purposes of this study. Some of the engineering judgement rationale behind the selection of individual module parameters are discussed in the Appendix to this section.

Engine parameters such as compressor airflow, pressure ratio, pressure ratio per stage, number of stages and engine thrust to weight ratio were plotted versus manhours per repair in an attempt to correlate JT3D, JT8D and JT9D low and high compressor data points. None of the individual parameters were adequate to explain the manhours per repair trend. **Therefore, various combinations were tried.**

The parameter that best describes the trend in the low and high compressors is the product of compressor tip speed squared (u_t^2), compressor diameter (dia.), and the number of compressor stages. The compressor tip speed is a technology factor, the diameter a size factor, and the number of stages a complexity factor. Figure III-18 shows this curve for the low and high compressors.

In the fan/low compressor, the JT8D and JT9D are very close in manhours per repair. The JT9D is much larger in diameter but has a lower tip speed and has two less stages than the JT8D with the net result of being very close to the JT8D in its manhours per repair value. The JT3D, however, has two more stages than the JT8D and a larger diameter

which explains the higher manhours per repair value. The JT9D high compressor has a high parameter value because it has a larger diameter and four more stages than either the JT3D or JT8D. It is expected that as the JT9D accumulates more time its manhours per repair will increase due to age affects and its manhour value will move closer to the trend line. The JT3D and JT8D have identical diameters and number of stages with the JT3D having a lower tip speed which is why the JT3D has the lowest manhour per repair value.

On plotting various parameters versus the manhours per repair for the diffuser case, none of the parameters provided a good correlation with actual experience. As can be seen on the bar graph in Figure III-19, the 3D and 8D are close together and quite high when compared to the JT9D. It is felt that this is due to the different design and construction techniques employed in the JT9D that were a direct result of JT3D and 8D diffuser case experience. While all of the cases are close in size, the 9D is heavier. A new construction technique was responsible for reducing strut fillet weld cracks by moving the weld out of the strut/wall intersection using integrally forged strut stand-ups. As the JT9D diffuser cases accumulate more hours and cycles, the manhours may increase but they are not expected to rise to the level of the 8D and 3D.

The combustor was another section where plotting the manhours per repair against various combinations of technology, size and complexity parameters did not yield a satisfactory correlation. It appears that construction and design details of the combustor are the governing factors that determine the manhours per repair for this section. The 3D has a can-annular combustor design that is larger in diameter than the 8D can-annular design but of the same length. While the 3D has 8

cans per engine and the 8D has 9 per engine, the 8D is much simpler and has less surface area. This accounts for the lower manhours per repair for the 8D, as shown in Figure III-19A even though the 8D has a higher turbine inlet temperature (1720°F) than the 3D (1600°F). The JT9D combustor is an annular design and while having less surface area than the 3D and 8D designs, its overall complexity, increased temperature and diameter are the driving forces behind the higher manhours to repair.

In the high and low turbine areas, a plot of the product of the square root of turbine inlet temperature, number of stages, and diameter versus manhours per repair show a good correlation with actual data. This plot is presented in Figure III-20. In the high turbine area, the JT9D manhours per repair are substantially higher than the 3D and 8D. This is reasonable considering its higher turbine temperature, two stages versus one for the 3D and 8D, and its larger diameter. In the low turbine, although the 9D still has the highest manhours per repair, the actual manhours are much closer together. Here the four stage JT9D low turbine has only one stage more than the three stage 3D and 8D low turbines. This represents a smaller percent increase (33% versus 100%) than for the high turbine section. It is expected that the JT9D manhours per repair will increase as the engine accumulates more time due to age affects and its point on Figure III-20 will move closer to the trend line.

b. Mean Time Between Repair

The mean time between repair of the six sections of the engine was also analyzed and compared with one another in Figures III-21 through III-29. The charts show mean time between repairs for the actual flight lengths and also adjusted to a common flight length. A value

of 1.25 hours per flight was chosen since this is the cycle for the advanced airplane and engine that was analyzed during Task II of this study. Analysis of American Airlines data for the JT3D and 8D indicates that module repair rates vary with flight length in the same proportion as the engine removal rates. The variation of the engine mean time between removals with flight length was shown in Figure III-8.

The mean time between repair of the fan/low compressor section is shown in Figure III-21. This shows that the 3D has the highest interval between repairs, with the 8D the next and the 9D experience to date the lowest. The predicted repair interval for the 9D, when adjusted for flight length, is slightly higher than the JT3D. Figure III-22 shows the mean time between repair for the high compressor. This plot again shows the 3D with the highest repair interval. This time, however, the JT9D, when adjusted for maturity and flight length, has a lower repair interval than both the 3D and 8D.

The mean time between repair of the diffuser section is shown in Figure III-23. The JT9D, when adjusted for maturity and flight length, shows a slightly higher repair interval than the 3D and 8D. Figure III-24 shows the combustor mean time between repair. The JT9D shows a lower repair interval than the 3D and 8D after adjusting for maturity and flight length.

The mean time between repair of the high turbine is shown in Figure III-25. Again, the JT9D has the lowest predicted repair interval.

Figure III-26 shows the repair intervals for the low turbine. In this instance, the predicted JT9D interval is higher than the 3D and 8D even though the turbine temperature is higher and there are four stages instead of three.

* Predicted JT9D-3A repair intervals were based on engineering analysis of upgraded 3A and -7 engine experience and component mechanical

The mean time between repair of the modules, corrected to the 1.25 hour flight length, were plotted versus various parameters in the same manner as the manhours per repair. The appendix to this section presents the rationale behind selection of the individual module parameters. As in the manhours per repair correlation, the mean time between repair parameters should not be considered as the only possible correlation, but the parameters derived are considered to be reasonable and meaningful from an engineering standpoint. The fan/low compressor and high compressor mean time between repair data is plotted, as shown on Figure III-27, versus the product of compressor exit temperature, compressor tip speed and pressure ratio per stage. The fan/low compressor of the JT9D is slightly higher than the 3D due to its lower tip speed and exit temperature. The JT8D has the highest tip speed and pressure ratio per stage, thus resulting in the lowest mean time between repair value. For the high compressor, the JT9D is very close to the 8D with the 8D having a slightly higher value due to its lower exit temperature and pressure ratio per stage.

No parameters were found that provided a good correlation of mean time between repair for the diffuser section. The JT9D has the highest repair interval due to its simpler design and improved construction techniques.

The parameter of combustor temperature rise ($T_{T \text{ exit}} - T_{T \text{ inlet}}$) provides a good correlation of combustor mean time between repair, as shown on Figure III-28. The JT9D, with the highest temperature rise, has the lowest repair interval.

The high and low turbine mean time between repair data are plotted, as shown on Figure III-29, versus the product of the square root

of the turbine inlet temperature, the turbine expansion ratio, tip speed and the number of stages in the turbine $(\sqrt{T_{T \text{ in}}})(\frac{P_{T \text{ in}}}{P_{T \text{ out}}})(U_T)$ (#Stg.). The JT9D high turbine has a significantly higher value of this parameter than the 3D and 8D. The JT9D has one more stage of turbine, higher turbine expansion ratio, and higher turbine inlet temperature resulting in the lowest repair interval. The JT9D low turbine has a higher mean time between repair than the 3D and 8D even though they are all close in parameter value. A major reason for the higher repair interval for the 9D low turbine is the modular construction. This permits removal of the low turbine to gain access to the high turbine and combustor without disassembling the module. In the JT3D design, the low turbine must be removed stage by stage to gain access to the high turbine. The modular construction allows the condition of each module to dictate its own repair interval.

A reasonably constant relationship was found to exist between mean time between engine removal and the most frequently repaired module mean time between repair (Figure III-29A). This relationship suggests that, for a given engine, the mean time between engine removal is approximately 83% of the mean time between removal of the most frequently repaired module.

D. Engine Maintenance Material Cost

Maintenance Material Cost (MMC) is a dynamic complex parameter that must be strictly defined as to the conditions under which it will be measured. Any measured value on a calendar basis is strongly influenced by the level of maturity of the subject engine, the mix of engine/part ages in a fleet, rates of incorporation of problem fixes, maintenance

policy of the airline, etc. An attempt is made in the study to adequately control these factors by basing the conclusions primarily on mature engine experience (JT3D and JT8D) at one airline (AA) and by using immature engine experience (JT9D) only as support in a general way for any resulting conclusions.

1. Maintenance Material Cost for Complete Engine

The maintenance material costs per engine flight hour for the three basic engines are shown in Figure III-30 versus years from start of service. Applying the price escalation correction takes away some of the "halo effect" that results from remembering the cost associated with early JT3D and JT8D maintenance. Even with this correction, the JT9D costs are higher than the earlier engines at the equivalent point in their service experience. However, one must remember that the JT9D is also significantly larger and more expensive than the earlier engines, and produces two to three times as many pay-load-miles per hour. Figure III-31 presents the maintenance material cost per flight hour trend when normalized by engine price, and shows the JT9D cost to be significantly lower on this basis than earlier engines.

The material cost data presented in Figures III-30 and III-31 shows considerable variation depending on engine type. In order to obtain a better understanding of the causes of the variation, the effects of different engine repair rates were considered by dividing the material costs/hour by the corresponding number of engine repairs/hours. The resulting material costs per repair of the three engines are plotted versus time in service, Figure III-32. These curves show a characteristic of increasing rapidly in the early years of service, then leveling off and staying relatively constant in the later years.

The early rise occurs as time accumulates on the engine parts and some premature failures occur. Product improvement programs eliminate the causes of these premature failures and extend the lives of the parts, resulting in the leveling off of the early rise. The curve might be expected to drop in later years as the parts and the maintenance approach are improved and refined. This drop does not occur because the time between repair is increasing as the engine matures, which means that more extensive repair and replacement of parts is required at each repair. The increasing time between repair is indicated by the decreasing engine removal rate with time as shown in Figure III-7.

If the material cost per repair is normalized by dividing by engine price, the spread between the three engines is reduced significantly as shown by Figure III-33. It should be noted from Figure III-33 that average material cost per repair/price for the first five years is reasonably consistent at about 75% of the mature value.

2. Breakdown of Material Cost by Module

To determine the relative contributions of the various sections of the engine to the total maintenance material cost, detailed American Airlines records for 1969-72 were analyzed for the JT3D and JT8D; and 1972-73 records for the JT9D. The material cost data used in this discussion includes three different types of material: repairable parts, expendables, and life limited parts. The cost distributions among these types are shown in Figure III-34 for each of the three engines. Expendable material cost breakdown was not available for the JT9D.

Figure III-35 shows the average material cost per flight hour for each of the three engines, broken down by modules. The modular breakdown is easier to understand on a percentage basis, as presented in Figure III-36. Note that the JT3D and JT8D costs are fairly evenly distributed among the modules, while the JT9D data shows a large portion of its cost in one module, the high pressure turbine. The JT9D distribution is expected to become more evenly distributed when the engine matures, as shown by the "Mature JT9D" bar.

The module costs per hour can be analyzed on a cost per repair basis in the same way that the total engine material costs were represented in the previous section. The analyses were performed on an average basis to smooth out yearly variations in the computed values. The module mean time between repair data used in the calculations is the same as that presented in Figure III-21 through -26 in the Maintenance Labor discussion.

It was observed earlier that dividing total engine material cost per repair by engine price reduces the data scatter among the engines. The same principle was applied to the module material cost per repair values by dividing by "module price", defined herein as the total spare parts price of the prime high cost parts within the module. This was found to be more satisfactory than using the overall module price. The prime high cost parts are those parts which are replaced frequently enough and are expensive enough so that they, in essence, control the cost of ownership of the module. These parts are listed for each module in Figure III-37. Some high priced parts such as cases are almost never scrapped so they do not appear on the prime high cost list. When the average cost of the parts replaced at each module repair is divided by

the price of a set of prime high cost parts, the result is an indication of the percent of the total value of the set of parts that is being replaced each time the module visits the shop. Since the prime high cost parts in all three engines are similar in nature (but sometimes widely different in price, as cooled versus uncooled turbine blades) it seems logical that the same average percent might be replaced each visit in any engine. If the average modular cost per repair is then normalized by dividing by the "module price" as previously described, the result is a fairly constant level for comparable modules of the JT3D, JT8D and predicted mature JT9D, as shown in Figure III-37A.

The six modules mentioned above, and whose prime high cost parts are described in Figure III-37, contribute a major portion of the engine MMC although their aggregate value is little over half the total engine value based on spare parts prices. The cost of other miscellaneous parts replaced at each engine repair is 17%, 15% and 7% the total MMC/EFH for the JT3D, 8D and 9D engines respectively. Although the JT9D level is currently 7%, it is expected that the miscellaneous parts will become a larger portion of the total as the engine matures. It is estimated that the miscellaneous parts in the mature JT9D will account for approximately 11% of the total MMC/EFH.

The apparent relative consistency of the MMC per repair/price values for a given module of the three engine types suggests that a typical value could be selected for each module to predict the maintenance material cost of a mature advanced engine, as required in Task II.

E. Installation Maintenance Cost Trends

1. Power Plant Package Maintenance Cost

Direct Maintenance cost data was obtained from American Airlines (AA) consisting of line and shop labor, shop material and outside services costs for the 707, 727, and 747 airplanes and engines (JT3D, JT8D and JT9D-3A respectively). Line material costs are very small and were ignored. Figures III-38-40 illustrate the relationship of the power plant direct maintenance costs to the total airplane direct maintenance costs for the 707, 727 and 747 using 1972 data. These data compared favorably with CAB required cost data supplied by AA on CAB Form 41 and with fleet average data published by the CAB from all domestic airlines. Detailed line maintenance data from another airline was used to sort out installation or Quick Engine Changes (QEC) component and basic engine component maintenance costs by ATA system. This distribution was used as a guide to sort out installation and basic engine shop labor and material and outside service costs. Table III-1 lists the distribution used for each airplane. Figures III-41-43 illustrate the relationship of installation to basic engine and also identify the high maintenance cost installation systems. The installation maintenance costs represent only 11 to 20% of the total power plant direct maintenance cost and each airplane operating at its own average flight length.

For the three aircraft studied, the high maintenance cost systems in the installation are ATA 71 Power Plant - General, ATA 78 Exhaust and ATA 80 Starting.

ATA 71 maintenance costs consist primarily of engine replacement effort on the line and QEC build-up and tear-down labor and material usage. Other maintenance costs are expended in the repair of the side cowl and inlet. ATA 71 costs are largely dependent on the engine removal rate along with removal, build-up and tear-down labor and material effort.

ATA 78 costs consist primarily of thrust reverser maintenance. If an aircraft has separate primary and fan thrust reversers as in the 707 and 747, the thrust reverser maintenance costs appear to double

III-
TABLE 1

MAINTENANCE COST DISTRIBUTION
BY PERCENT

<u>ATA</u>	<u>707</u>		<u>727</u>		<u>747</u>	
	<u>BASIC ENG.</u>	<u>INST'L</u>	<u>BASIC ENG.</u>	<u>INST'L</u>	<u>BASIC ENG.</u>	<u>INST'L</u>
71	-	100	-	100	-	100
72	100	-	100	-	100	-
73	70	30	80	20	85	15
74	80	20	95	5	99	1
75	60	40	45	55	50	50
76	-	100	-	100	-	100
77	5	95	15	85	5	95
78	-	100	-	100	-	100
79	30	70	30	70	20	80
80	-	100	-	100	-	100

those of an aircraft with a single thrust reverser such as the 727. Other maintenance costs are expended in the tail pipe and exhaust plug.

ATA 80 consists primarily of the maintenance costs expended on the pneumatic starter and start valve. Other costs are expended on the start switch and associated electrical components and wiring.

AA has all maintenance of the 747 QEC and basic engine performed by outside services. CAB Form 41 allows all outside service costs to be charged as direct costs. Therefore, in all presentations of the 747 power plant maintenance cost data, labor costs have been corrected to AA's rates and all fees and taxes removed to make them comparable to the 707 and 727 power plant data. As a consequence, total airplane or power plant maintenance costs will not compare to CAB Form 41 data.

All total airplane data presented in Figures III-38 through 43 are not adjusted to the same average flight length. The average flight lengths represented for the 707, 727 and 747 are 2.2, 1.2 and 3.5 flight hours respectively. Detailed maintenance costs in the following sections have been adjusted to a 1.25 flight hour average flight length which coincides with the flight length of the Task II study airplane. The adjustment to installation maintenance costs for flight length is made using the curves in Figures III-44 and 45. These curves were developed from a study using actual data made available by an airline flying 727's on two distinct and separate route systems, Reference 1.

For comparison purposes maintenance costs have been normalized on a seat-mile basis and are listed in parentheses on the charts.

2. Distribution of Power Plant System Maintenance Costs

The distributions between basic engine and the installation of each element of maintenance cost in terms of dollars per engine flight hour are shown in Figure III-46-49.

The basic engine includes the bare engine produced and assembled by the engine manufacturer and such components as the fuel control, fuel pump, fuel heater, fuel-oil cooler, oil tank, ignition system, some engine instrument probes and engine air controls.

The installation includes all components installed on the engine by the airframe manufacturer and identified in the ATA systems 71 through 80. These components include the inlet, side cowl, thrust reversers, all engine instrumentation and transducers, starting system, service bleed system and control systems. The installation maintenance cost data exclude premature replacement and all maintenance repair costs on the constant speed drive, AC generator and the hydraulic pumps which are run off the engine gear box, because these costs are accumulated in the appropriate airframe ATA systems and not in propulsion. Only the maintenance costs incurred to remove or install these components during power plant QEC tear-down or build-up are included.

As shown, line labor cost is distributed about 50-50 between installation and basic engine. The total shop labor costs include 20-40% charged to the installation as illustrated in Figure III-47. About 10 to 20% of the shop material costs are spent on the installation as shown on Figure III-48. Outside services vary greatly depending on the airlines facilities, capabilities, and management and maintenance policies. The dollars spent represent a small portion of the total and can be ignored. Figure III-49 illustrates the outside services costs as incurred by American Airlines and is included for information only. All data are in 1972 dollars and the 707 and 727 are five year averages (1968-1972) while the 747 data is just 1972.

3. Power Plant Installation Costs

As indicated in the introduction, three systems (ATA 71 Power Plant - General, ATA 78 Exhaust, and ATA 80 Starting) account for approximately 75% of the power plant installation total direct maintenance cost. This section describes the maintenance costs for each of the

above systems and the remaining ATA systems. The labor costs are plotted at their fully allocated rates to make them comparable to material costs, which include indirect as well as direct charges. All 707 and 727 data are based on a five year average (1968-1972) and the 747 is based on the year 1972 only. All costs are adjusted to 1972 dollars.

3.a ATA 71 Power Plant General - Maintenance Costs

Figure III-50 presents the breakdown of all maintenance costs for ATA 71. This system represents approximately 12% of the total power plant costs and 45% of the installation costs.

The major portion of the line labor spent is in engine change. Airline experience indicates it averages 25 manhours to change an engine on the 727, 30 manhours on the 707 and 44 manhours on the 747 including engine trim. Using the engine removal rate and multiplying by the manhours per removal and the labor rate in dollars will provide a good estimate of the line labor cost for ATA 71. Some removals are accomplished in a dock during overnight stops or periodic checks, resulting in the costs being charged to shop rather than line maintenance which can account for some discrepancy when checking actual data.

In the shop, the major portion (70%) of the maintenance costs are expended in the tear-down and build-up of QEC's. Airline experience indicates the tear-down and build-up manhours averages for the 707/JT3D, 727/JT8D and 747/JT9D are 35 and 210, 20 and 100, and 100 and 300 manhours, respectively. As in the line maintenance labor costs, the shop labor costs can be estimated by multiplying the build-up and tear-down manhours by the labor rate and engine removal rate. The remaining 30% is expended in repair of inlet and side cowl primarily and can be added as an increment.

The shop material is a small item of cost and results in just 10% of the total system costs.

Outside service is a matter of management and maintenance policy and is difficult to consider in the general case. As illustrated by **Figure III-50**, some outside service costs were expended on the 747 based on American Airlines data.

For comparison purposes, Figure III-51 is included and illustrates maintenance costs using direct labor rates.

Since the maintenance costs in this system are primarily affected by **engine removal rate**, **Figures III-50A and 51A** are included to illustrate the maintenance cost per removal.

3.b ATA 78 Exhaust - Maintenance Costs

Figure III-52 presents the breakdown of the all maintenance costs for ATA 78. This system represents approximately 6% of the total power plant costs and 25% of the installation costs.

The major portion (Approximately 85%) of the total maintenance costs charged to ATA 78 are expended in the thrust reverser system. The data indicates that for a power plant installation consisting of both a fan and primary thrust reverser, as on the 707 and 747, the maintenance costs are approximately double those installations with just one thrust reverser, as in the 727. With this as a consideration, **Figure III-51** indicates a constant maintenance cost increment per reverser could be used for this system.

For comparison purposes Figure III-53 is included and illustrates maintenance costs using a direct labor rate.

3.c ATA 80 Starting - Maintenance Costs

Figure III-54 presents the breakdown of all maintenance costs for ATA 80. This system represents approximately 1% of the total power plant costs and 6% of the installation costs.

The major position (approximately 75%) of the total maintenance costs charged to ATA 80 are expended in the pneumatic starter and start valve. As noted above these costs are a small portion of the total power plant and installation costs. As indicated by Figure III-54, a constant maintenance cost increment could be used for this system. For comparison purposes, Figure III-55 is included and illustrates maintenance costs using a direct labor rate.

3.d All Other ATA Systems - Maintenance Costs

The remaining ATA systems that include installation maintenance costs are ATA 73 Engine Fuel and Control, ATA 74 Ignition, ATA 75 Air, ATA 76 Engine Controls, ATA 77 Engine Indication, and ATA 79 Oil. These six ATA systems represent approximately 5% of the total power plant costs and 24% of the installation costs. Figure III-56 presents the breakdown of all maintenance costs for the sum of all the remaining power plant ATA systems.

The 747 costs in these systems were high due primarily to new engine instrumentation concepts. Considering the above, the maintenance costs expended for these ATA's could be treated as an incremental cost.

For comparison purposes, Figure III-57 is included and illustrates maintenance costs using a direct labor rate.

Reference

1. A8491R1 "Distribution of Maintenance Cost Per Cycle and Per Operating Hour, "Operation Economics, Boeing Commercial Airplane Company, dated January, 1973.

F. Dispatch Reliability

1. Introduction

Dispatch reliability is one of the significant factors affecting airline profitability. In part, dispatch reliability achievements are a reflection of the aircraft and systems reliability. In this study, only delays and cancellations for mechanical reasons will be discussed and analyzed, although these are a small part of the total delay/cancellation causes. These interruptions are translated into a percentage figure sometimes referred to as Mechanical Schedule Reliability. Figure III-58 shows the historical trend of Mechanical Schedule Reliability with months in service for 707, 727, 737 and 747 aircraft and includes both airframe and power plant system caused schedule interruptions. The 707 and 720 curves are smoothed using monthly average data. The 727, 737 and 747 data are monthly averages unsmoothed.

The data indicates there is improved mechanical reliability as the flight length is shortened. Probable reasons for this are as the flight length increases less maintenance is deferred and (possible restricted use of the Minimum Equipment List.) There is also an increase in complexity with the increase in flight length such as larger aircraft, more engines and more systems required, which can cause an increase in delay rate or reduced mechanical reliability.

When comparing the various aircraft, if the interruption costs are put on a productivity basis, (interruption costs per seat-mile) the larger aircraft are competitive. (See numbers in parentheses on Figures III-65-68.)

The following sections will discuss schedule interruption rates, defining the power plant system's contribution to the total airplane, showing the high power plant installation system contributors and interruption costs, identifying high contributors in both the basic engine and the installation.

2. Interruption Rates

Interruption data were reviewed for the year 1972 from airline data that summarily defines the cause. This data was used to identify, in the power plant systems, those interruptions which relate to the basic engine or to the installation. Due to lack of detail, the allocation of some interruptions may be questioned. However, it is felt that the distributions are reasonably accurate and are comparable between aircraft.

Figure III-59 illustrates the distribution between basic engine and installation for the 707, 727, 737 and 747. From 40 to 55% of the interruption rate is identified as installation chargeable. Contrary to the maintenance cost story which showed the installation as a small contributor to the power plant maintenance cost, the installation is almost equal to the engines as a contributor to schedule interruptions.

The analysis of all interruptions identified high schedule interruption contributors in the power plant installation portion of the 707, 727, 737 and 747. Figures III-60-63 show that portion of the total airplane interruptions that are power plant chargeable and identify the high power plant installation contributors. In all four aircraft, ATA 78 and 80 are identified as high contributors. The interruptions charged to ATA 78 Exhaust are 99% thrust reverser caused. ATA 80 Starting schedule interruptions are primarily starter and start valve caused. The other ATA's identified as high contributors are ATA 77 and 79 which are primarily instrumentation caused.

3. Interruption Costs

Schedule interruptions are acknowledged to impose considerable cost penalty on airline operations. In an effort to assess this penalty, American Airlines made estimates of interruption costs for each aircraft in their fleet for three delay time lengths (0 to 29 minutes, 30 to 59 minutes and 60 and over minutes) and for cancellations. The cost areas included were lost passenger revenue, passenger handling costs, crew salary costs, operating costs and analysis costs.

Table III-2 lists the costs used in this study by aircraft type.

TABLE III-2
COSTS FOR AVERAGE DELAY LENGTH (1972 \$)

<u>Type Aircraft</u>	<u>0-29 Min.</u>	<u>30-59 Min.</u>	<u>60 & Over</u>	<u>Cancellation</u>
707	90	225	1180	1535
727*	88	218	978	1272
737**	75	185	860	1120
747	155	395	1590	2065

* Average of 727-100 and 727-200

** Boeing Estimate Based on AA Data

The data analyzed included the length of each delay and identified cancellations so the above interruption costs could be applied.

Figure III-64 shows the split between basic engine and installation and indicates that the installation represents 35 to 45% of the estimated power plant systems interruption cost although the installation contributes 40 to 55% of the interruption rate.

The schedule interruption cost high contributors in the installation still appear to be ATA 78 Exhaust and 80 Starting in most cases as shown on Figures III-65-68. With the thrust reverser, starter, start valve, and engine instrumentation as the primary problem areas.

In this analysis, the basic engine was also studied to determine high contributors. As shown on Figures III-65-68 for all four airplanes, ATA 72 Engine and ATA 73 Fuel and Controls were identified as high contributors. High schedule interruption cost contributors also included ATA 79 (Oil) on the 707 and 747, and ATA 74 (Ignition) on the 727 and 737.

In reviewing the brief descriptions of reasons for interruptions charged to ATA 72, it is difficult to define the true problem causes because they are generally initial flight line diagnoses only. Some of the common statements used are as follows:

- a. engine vibration
- b. oil leak
- c. compressor stall
- d. high EGT
- e. burner can shift
- f. engine FOD

On the JT9D powered 747, more detailed problem source information can be obtained because of the extensive boroscope capability. Records indicate such intelligence as 1st. and 2nd stage turbine blades cracked, 2nd. and 8th. stage compressor blades damaged, etc.. It is still difficult to accurately identify and categorize problem areas because broad statements are still contained in the records and the resulting shop findings are not available.

The primary basic engine problem components in ATA 73 are the fuel control and fuel pump on all engines, P&D valve on the JT8D and Tt₂ probe on the JT9D. In the ignition System, ATA 74, the exciter box and ignition plug and lead are the problem components. The data indicate that the oil tank and oil pressure regulation are the major problem areas in ATA 79 Oil.

METHODOLOGY, DATA SOURCES AND ASSUMPTIONS1. Total Maintenance Cost for Complete Powerplant

The data source for this study was American Airlines CAB Form 41 and other maintenance cost and flight hour data for the 707, 727 and 747 aircraft. The costs were adjusted from "actual year" dollars to 1972 dollars using the escalation rates shown in Table III A-1. Outside Service (OSS) costs were escalated at the same rate as the direct labor. The material escalation represents 5% per year compounded. The direct labor costs were converted to fully allocated labor (FAL) costs by multiplying the direct costs by the ratio of AA's 1972 FAL rate to the direct labor rate. This ratio is 3.06.

American Airlines JT9D engines are maintained by Pacific Airmotive Corporation (PAC). The JT9D data were adjusted to remove the PAC management fee from the OSS charges. The labor portion of the PAC charges was also adjusted to reflect AA direct labor rates instead of the PAC labor rate. The equivalent AA direct labor costs were then adjusted to FAL in 1972 dollars as previously described.

2. Breakdown of Powerplant Maintenance Costs Into Installation and Basic Engine Which is Subdivided Into FAL, Material & OSS

The maintenance cost breakdown of the powerplant was obtained by multiplying each year's FAL, material and OSS costs for the powerplant by the following factors:

	<u>JT3D</u>		<u>JT8D</u>		<u>JT9D</u>	
	<u>BASIC</u> <u>ENGINE</u>	<u>INSTALLATION</u>	<u>BASIC</u> <u>ENGINE</u>	<u>INSTALLATION</u>	<u>BASIC</u> <u>ENGINE</u>	<u>INSTALLATION</u>
FAL	68%	32%	83%	17%	60%	40%
MATERIAL	70	30	85	15	85	15
OSS	70	30	85	15	75	25

These factors represent the average values obtained from analysis of the American Airlines maintenance cost data for 1968-72 for the JT3D, 1969-72 for the 8D, and 1972-73 for the JT9D.

3. Evaluation of JT3D, JT8D and JT9D Data

The goal of the evaluation was to correlate the JT3D, JT8D, and JT9D data to yield a trend that could be used to predict the maintenance cost elements of advanced engine designs. It is desirable to make the initial predictions as early as possible in the engine design process, since design changes to improve maintenance cost can be incorporated easily at this point. With this in mind, the correlations were made against engine parameters that are defined early in the conceptual design phase. All of the parameters used are available either directly or indirectly from the cycle matching calculation and the flowpath elevation, which are the first two steps of an engine design effort.

The sea level takeoff - hot day operating condition was chosen as the flight condition for the parameters used. This condition is in some respects the most severe encountered during operation. However, it is not the one at which the most time is spent. Ideally, all the conditions (takeoff, climb, cruise, landing) and the time spent at each should be considered in determining the mean time between repair for each module. However, time did not permit development of a projection model which would consider all of these conditions so the sea level takeoff - hot day condition was chosen as a simplifying assumption. The details of how and where certain of the correlation parameters were measured and/or calculated are described in the following sections.

Module Manhours Per Repair

Compressor Manhours Per Repair

The manhour per repair parameter derived for the compressors is the product of tip speed (ft/sec) squared (U_t^2), diameter (inches), and number of stages. In the case of the fan/low compressor, a value for the fan and low compressor for each engine was calculated separately and then added together to get the fan/low compressor parameter for each engine. This was necessary because the fan and low compressor data on the JT3D and JT8D engines were not recorded separately. The diameter used in the parameter calculations and in calculating the tip speeds was measured at the tip of the 1st stage blade in each section (fan, low & high compressors).

The use of tip speed in the parameter is referred to earlier in this report as a technology factor. The mechanical tip speed is also felt to be a good measure of structural requirements and sensitivity to unbalance. The JT8D has higher tip speeds in its compressors and has proven to be more sensitive to unbalance than the JT3D and JT9D. This increases the manhours per repair because of the special stacking, assembly and balance procedures required to reduce the likelihood of building an engine which will vibrate out of limits at test. Diameter and number of stages are size and complexity factors, respectively. Larger sizes mean increased part surface areas which increase inspection, repair and assembly manhours. More stages results in increased number of parts also increasing inspection, repair and assembly times.

Diffuser and Combustor Manhours Per Repair

It was not possible to correlate the diffuser or combustor manhours per repair data points with any performance or physical parameters or combination thereof. A qualitative analysis was performed based on the design features and construction methods of each engine to identify the areas of each diffuser and combustor section that contributed to or served to reduce the manhours per repair. These details are not defined in the early design phase of a new engine, but the evaluation can be made by assuming that the new diffuser and combustor will be similar to one of the existing designs. This assumption can be updated as more detailed information becomes available later in the design process.

Turbine Manhours Per Repair

The manhours per repair parameter derived for the turbines is the product of the square root of turbine inlet temperature ($^{\circ}\text{R}$), the number of stages and turbine diameter (inches). For the high turbine, the diameter is measured at the tip of the 1st stage blade whereas the diameter of the low turbine is the mean diameter of the turbine blade tips. As with the compressors, diameter and number of stages directly affect the manhours per repair. Turbine inlet temperature was measured at the combustor exit for the high turbine and at the high turbine exit for the low turbine. Temperature is a measure of technology and has a strong effect on turbine manhours per repair because increased temperatures mean increased cooling flow and/or cooling in additional stages. This increases the turbine structural complexity when such things as cooling air ducts, sideplates, dampers, blade cooling tubes, blade coatings and complex blade cooling hole schemes are required to keep metal temperatures within limits, prevent metal erosion and oxidation caused by the higher temperatures.

Module Mean Time Between Repair

Compressor Mean Time Between Repair

The compressor mean time between repair parameter is the product of the low compressor exit temperature ($^{\circ}\text{R}$), pressure ratio per stage (PR/STG) and tip speed (ft/sec). In this case, the tip speed used for the fan and low compressor is an average of their tip speeds, as computed for the manhours per repair parameter, weighted by the number of stages in the fan and low compressor. The tip speed computed for the high compressor manhours per repair parameter is also used for the high compressor mean time between repair parameter. The pressure ratio per stage is the average, computed by taking the overall pressure ratio of the compressor to the $1/N$ power ($\frac{\text{PR}}{\text{STG}} = \text{OPR}^{1/N}$), where N equals the number of compressor stages. The pressure rise over both the fan and low compressor was used for the fan/low compressor calculation.

The pressure ratio per stage and tip speed are measures of the compressor technology. Compressor exit temperature provides a measure of metal temperatures in the compressor. High tip speeds and pressure ratio per stage values require high speed airfoils that are highly loaded aerodynamically. Such compressors are more susceptible to erosion, foreign object damage (FOD) and bill of material object damage (BMOD). High tip speeds also increase rotating and static structural requirements with regard to blade loss and containment. Along with high temperatures this tends to decrease part lives notwithstanding the better materials employed.

Diffuser Mean Time Between Repair

As was the case with the manhours per repair, a correlation of diffuser mean time between repair data points and performance and physical parameters was not possible. Again, an analysis of the design features

and construction methods was necessary to qualitatively estimate the mean time between repair of this section.

Combustor Mean Time Between Repair

The combustor mean time between repair data points were correlated using the parameter of combustor exit minus combustor inlet temperature for each engine. This is the temperature rise across the combustor which, when increased, requires a combustor with a more complex cooling scheme, better materials and liner coatings. However, these better materials and coatings offer very little additional protection when cooling flow is interrupted or fuel nozzles begin to coke up. The resulting hot spots and streaking cause distortion, buckling and burning of the combustor walls that reduce the mean time between repair of the combustor. Hot spots and streaking are a typical failure mode in a combustor and with increasing combustor temperature rise are expected to cause more severe damage to the combustor when they do occur.

Turbine Mean Time Between Repair

The mean time between repair parameter derived is the product of the mechanical tip speed in ft/sec (U_t), the number of stages, the turbine expansion ratio ($\frac{P_{tin}}{P_{tout}}$) and the square root of turbine inlet temperature ($^{\circ}R$). The tip speeds are the same as the ones computed for the turbine manhours per repair parameter. As was the case with the compressors, the number of stages is a measure of complexity. An increase in the number of stages tends to reduce the repair interval because of the increased probability of failure. Tip speed provides a measure of structural requirements with higher tip speeds causing increases in rotating and static structural requirements, thus tending to reduce the repair interval due to more unknowns associated with higher stress levels. Temperature is a measure of technology in the turbine. Increased

temperature requires an increase in cooling flow, better materials and/or better cooling arrangements. The square root of temperature recognizes the more efficient means of cooling and better materials which are incorporated with higher temperature levels in the turbine. The turbine expansion ratio is a measure of the amount of work done by a turbine. High expansion ratios are the result of high pressure drops across each stage of the turbine which require highly cambered airfoils. Such airfoils are more susceptible to FOD, BMOD and erosion, thus tending to reduce the turbine repair interval.

Module Maintenance Cost per Repair/Price

The module maintenance material cost per repair/price parameter is a measure of the average percent of the module prime part price which is scrapped at each repair. Hence, the physical makeup of each module must be kept consistent between engine types if the parameter is to be meaningfully correlated for use in projecting module MMC.

The composition of the engine modules studied varied from engine to engine according to AA overhaul procedures. To obtain the desired engine to engine module consistency, certain module material costs and repair intervals were adjusted to reflect the content of module prime high cost parts given in Figure III-37.

The desired MMC per repair/price parameters were computed by dividing the revised module dollars per repair by the corresponding module prime high cost parts price (ref. Figure III-37A).

It should be recognized that consistency of the module MMC per repair/price parameter is proposed only for mature engine levels. While recent year AA JT3D and JT8D data could be used without adjustment, the JT9D

data utilized in the study had to be projected based on the immature engine trends combined with engineering predictions concerning improvements available and engine age effects.

RELATIVE DIRECT LABOR & MATERIAL RATES

<u>YEAR</u>	<u>LABOR</u>	<u>MATERIAL</u>
1961	2.236	1.710
1962	2.140	1.630
1963	2.047	1.550
1964	1.966	1.477
1965	1.887	1.407
1966	1.833	1.340
1967	1.679	1.276
1968	1.652	1.216
1969	1.494	1.158
1970	1.366	1.102
1971	1.059	1.050
1972	1.000	1.000

Table III A-1 . Labor and Material Escalation Factors

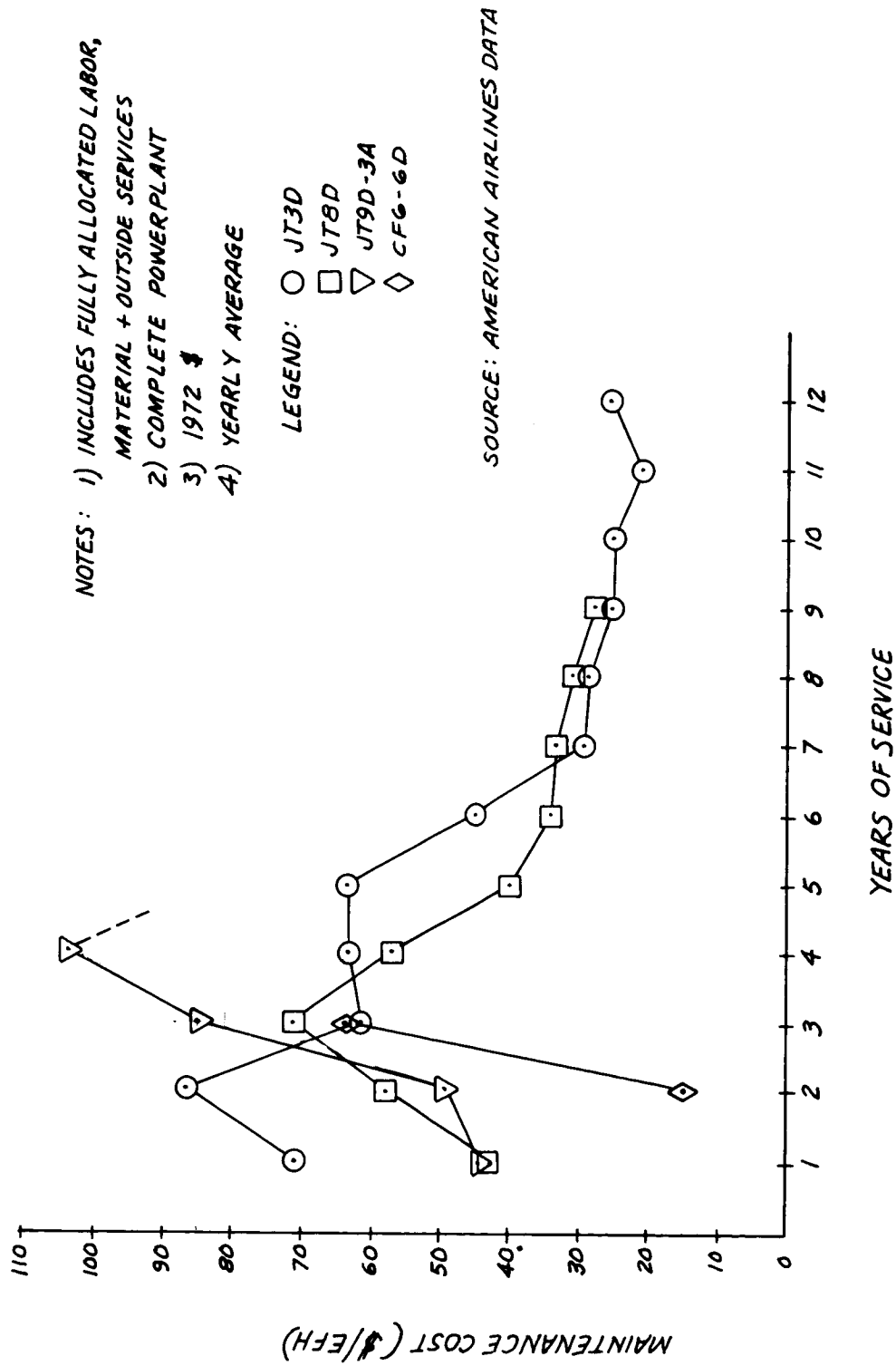
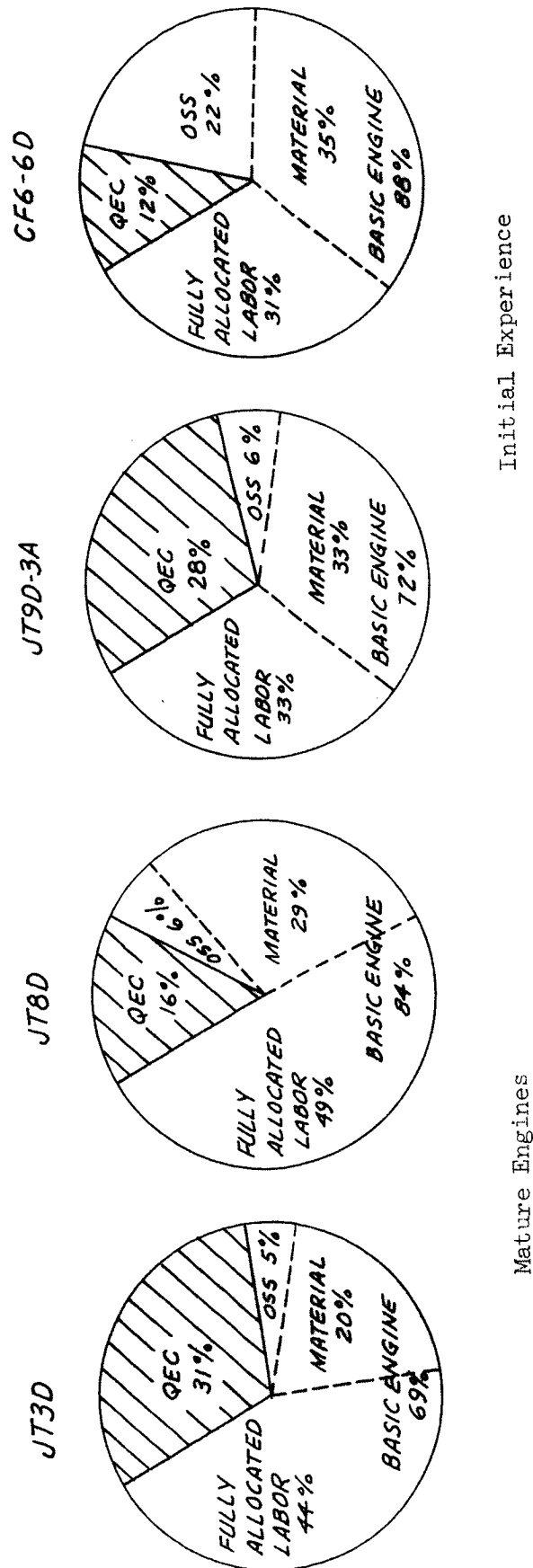


Figure III-1 Total Maintenance Cost of Complete Powerplant



REV. - 4-10-74

Figure III-2 Powerplant Maintenance Cost Breakdown

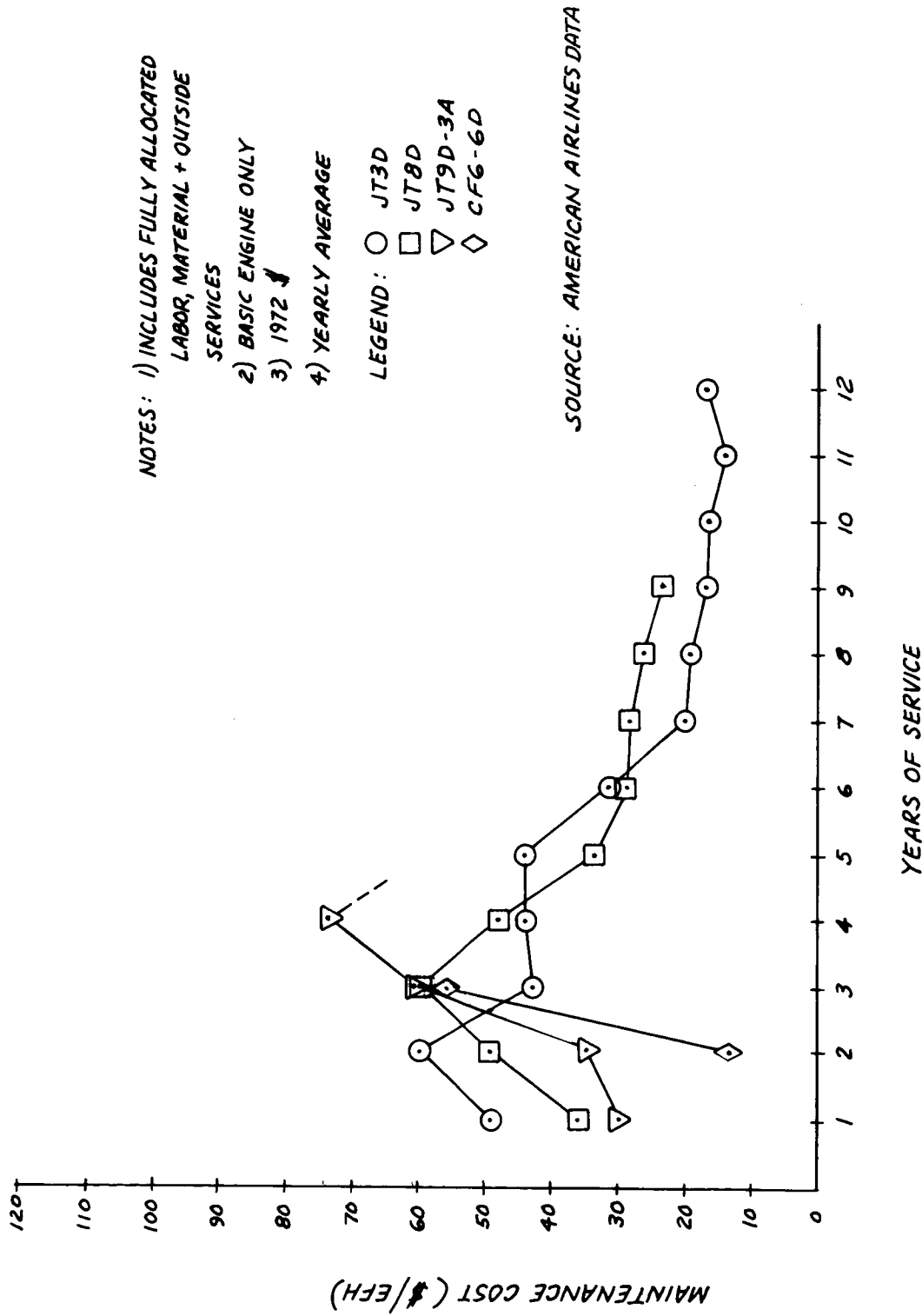


Figure III-3 Reduction of Total Maintenance Cost of Basic Engine With Maturity

REV. 4-3-74

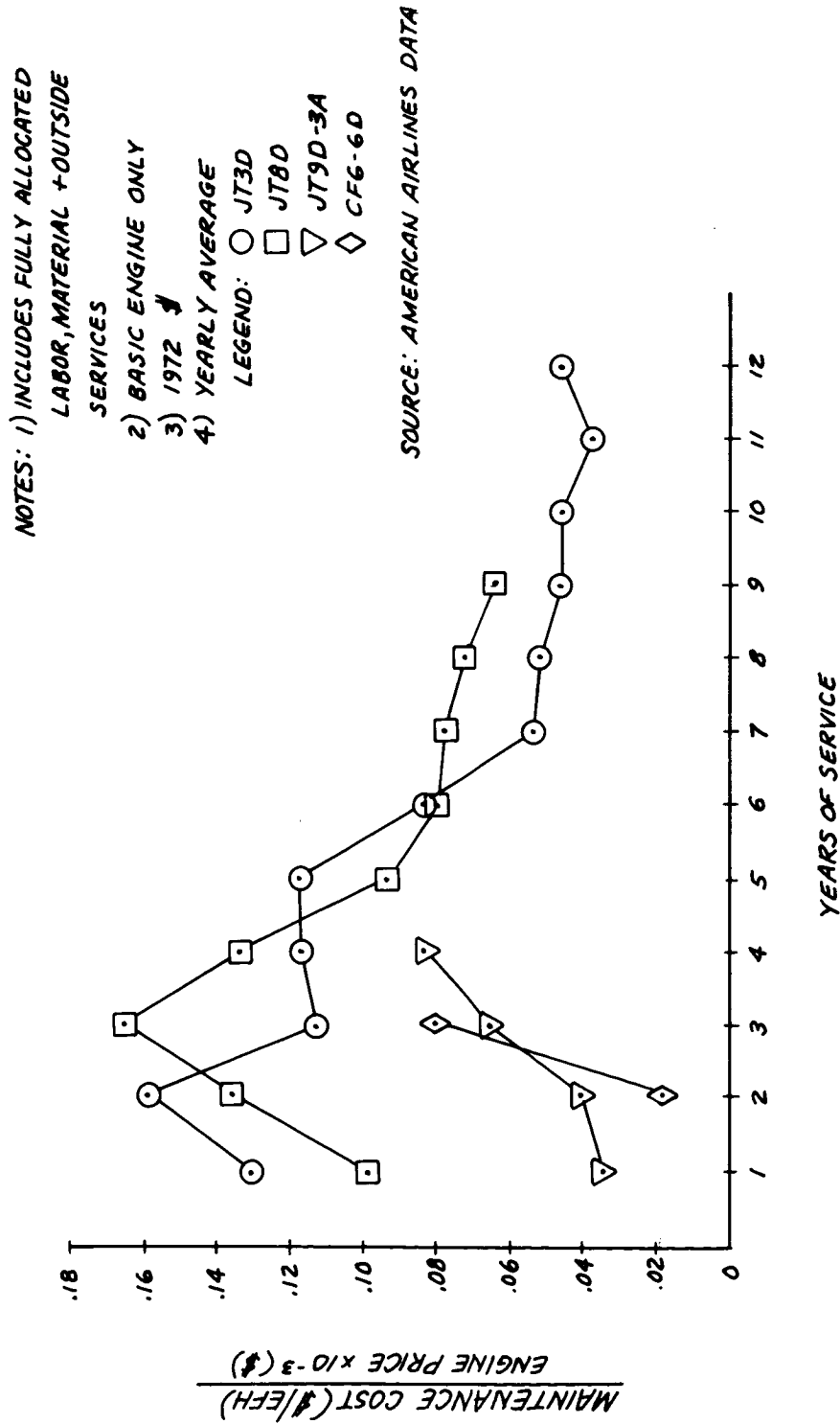


Figure III-4 Total Maintenance Cost Normalized to Engine Price

NOTES: 1) INCLUDES FULLY ALLOCATED
LABOR, MATERIAL + OUTSIDE
SERVICES

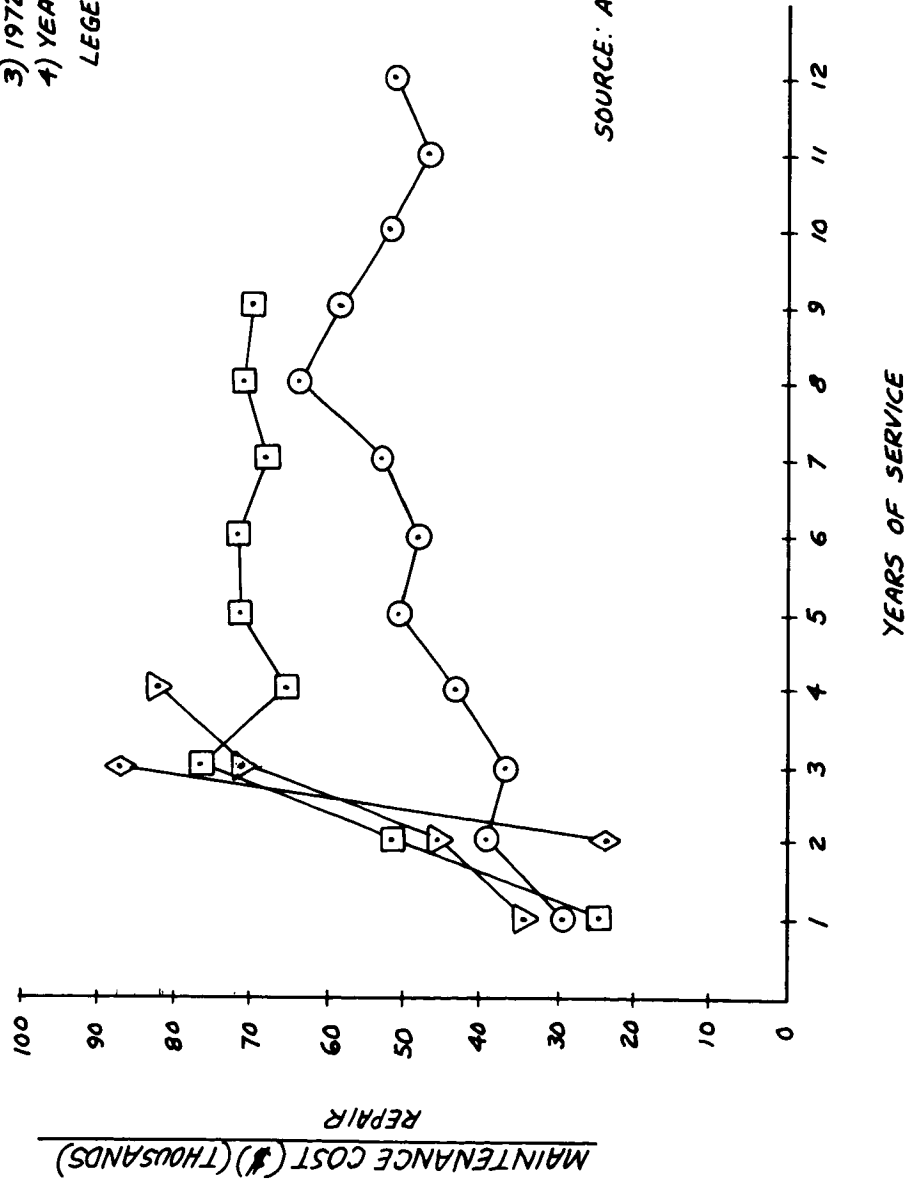
2) BASIC ENGINE ONLY

3) 1972 \$

4) YEARLY AVERAGE

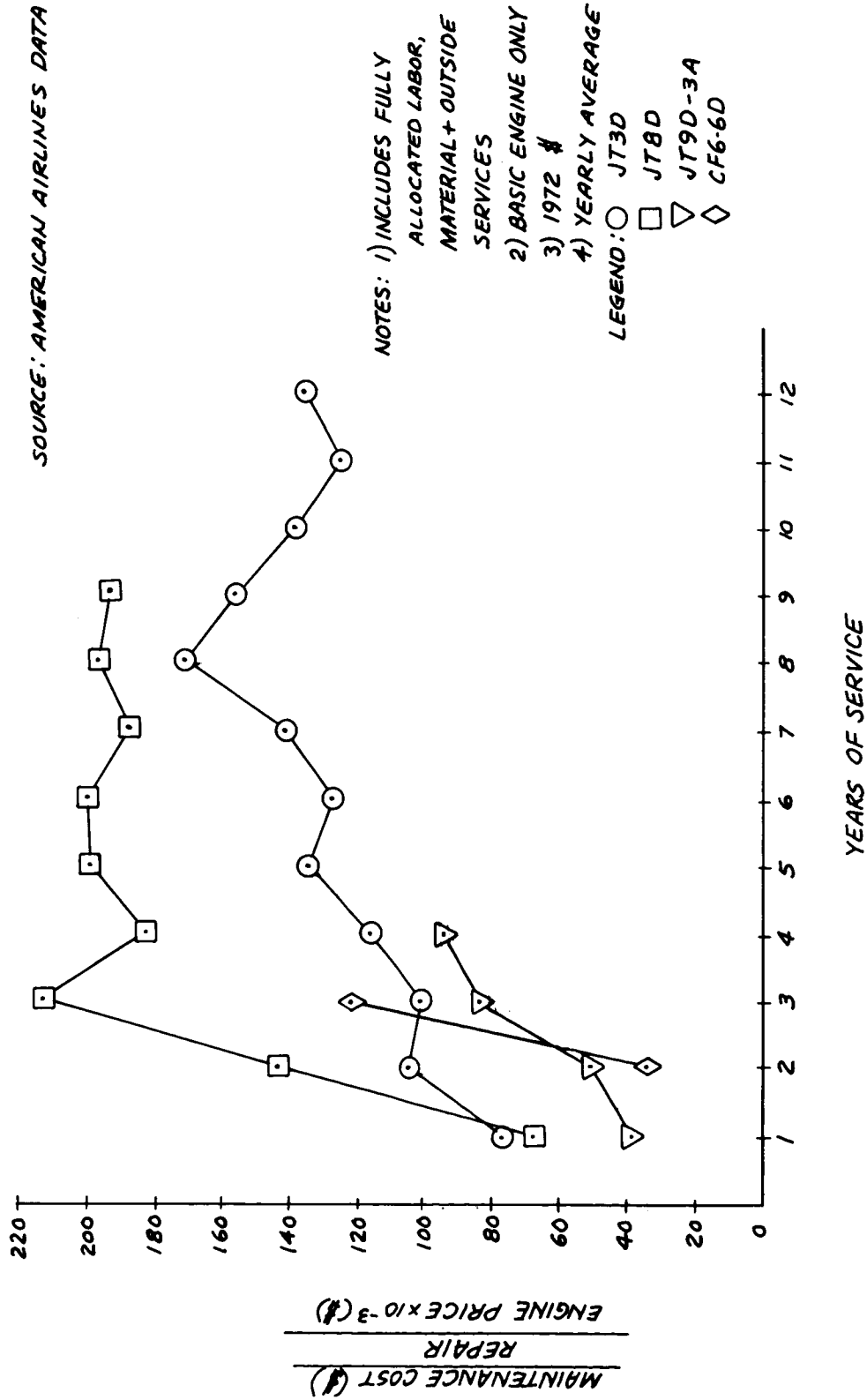
LEGEND: ○ JT3D
□ JT8D
▽ JT9D-3A
◇ CF6-6A

SOURCE: AMERICAN AIRLINES DATA



REV. 4-3-74

Figure III-5 Cost Per Repair Increase to Mature Level



REV. 4-3-74

Figure III-6 Cost Per Repair Normalized to Engine Price

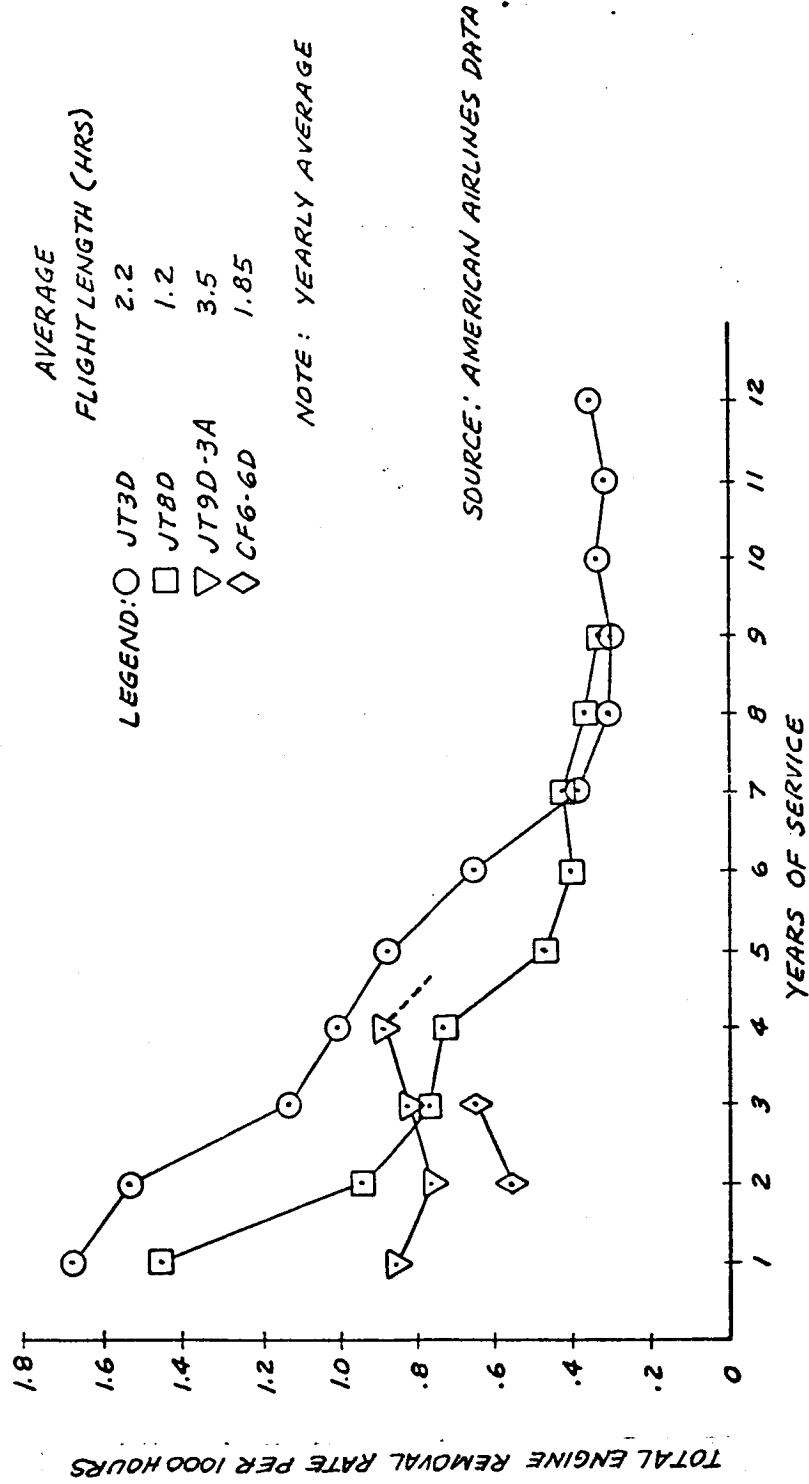
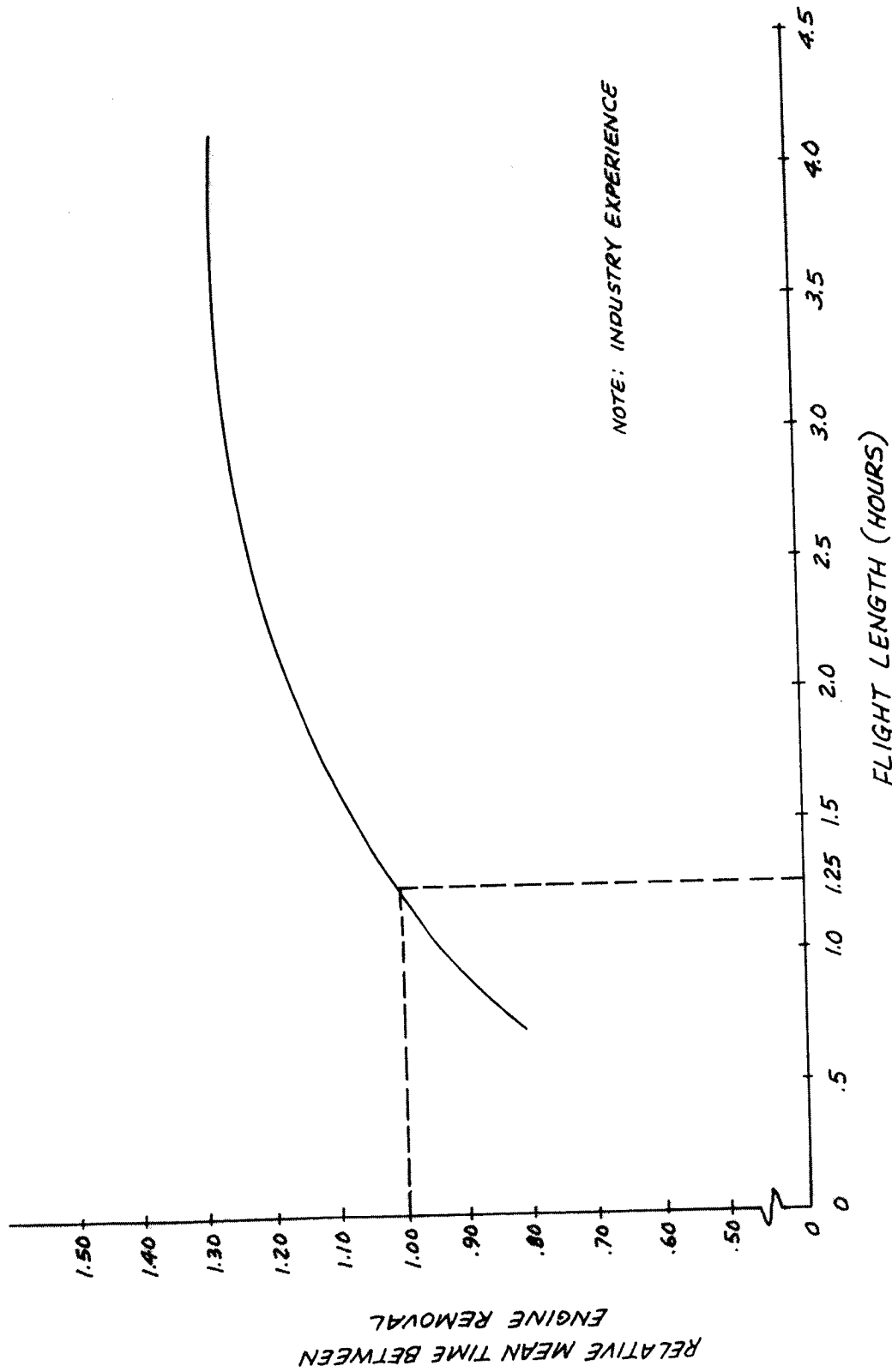


Figure III-7 Removal Rate Improves to a Mature Level

REV. 6-3-74



NOTE: INDUSTRY EXPERIENCE

Figure III-8 Mean Time Between Engine Removals Increases With Flight Length

REV. 6-3-74

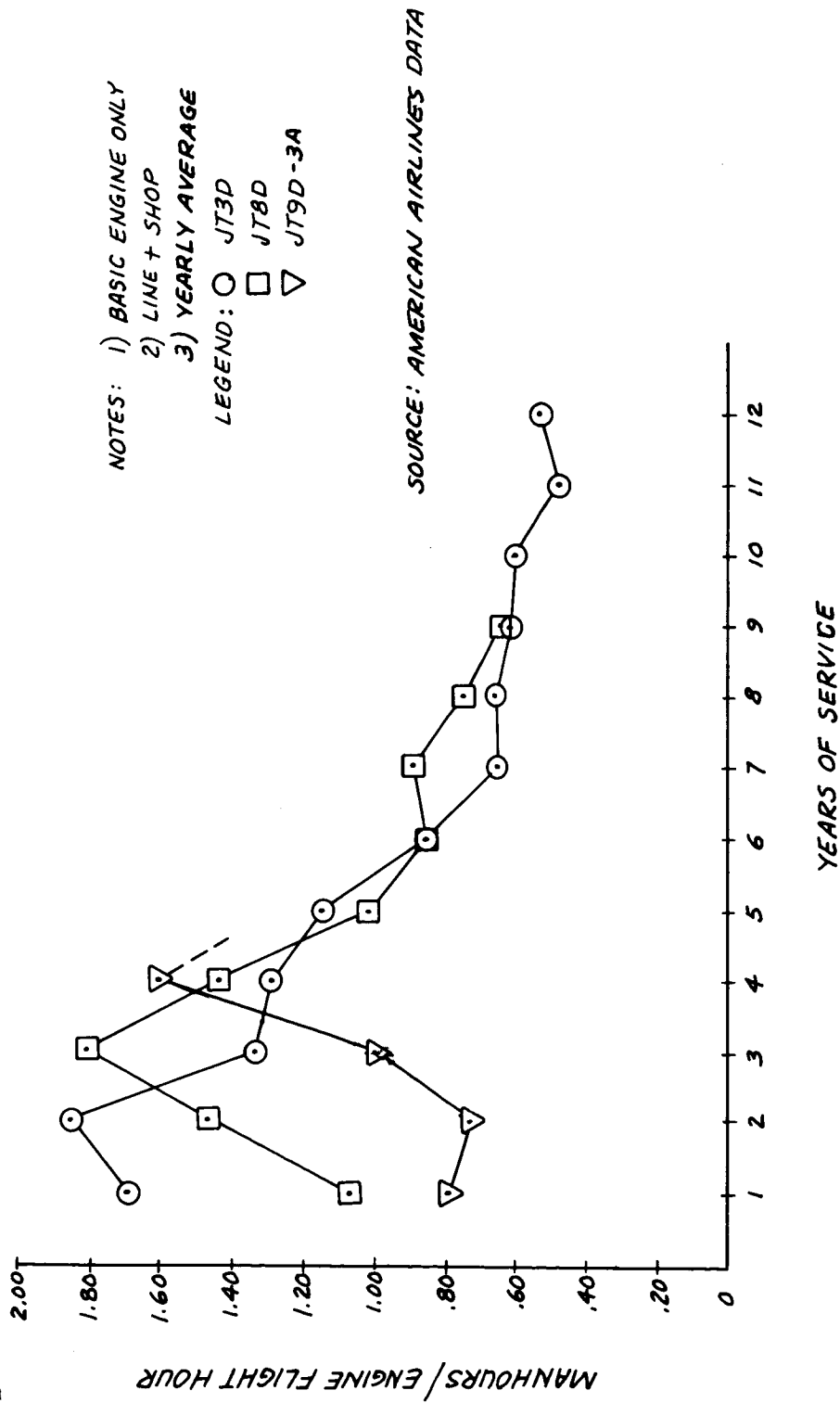
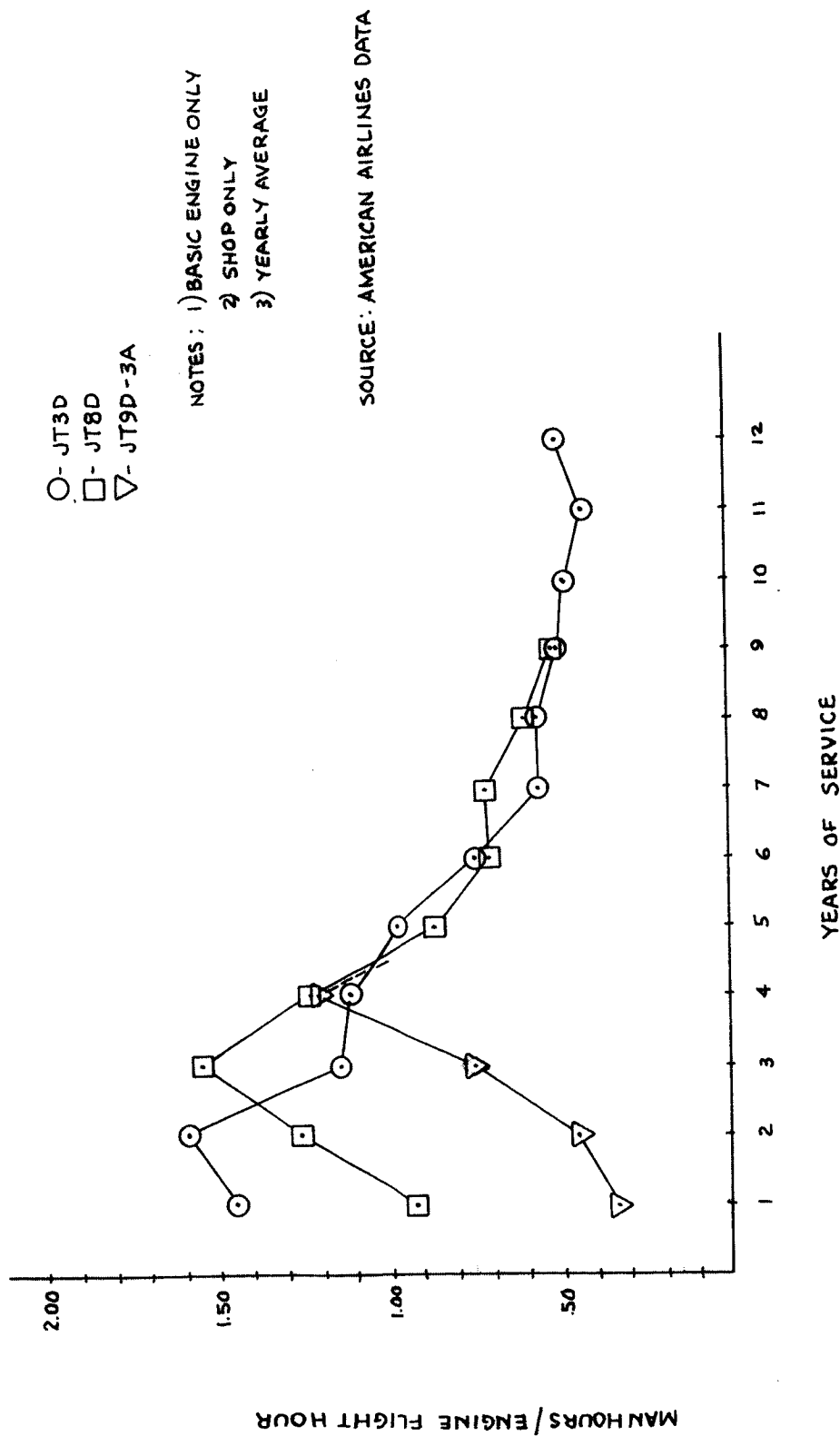


Figure III-9 Maintenance Labor Cost Decreases as the Engines Mature



REV-4-4-74

Figure III-9A Shop Maintenance Labor Cost Decreases to Mature Level

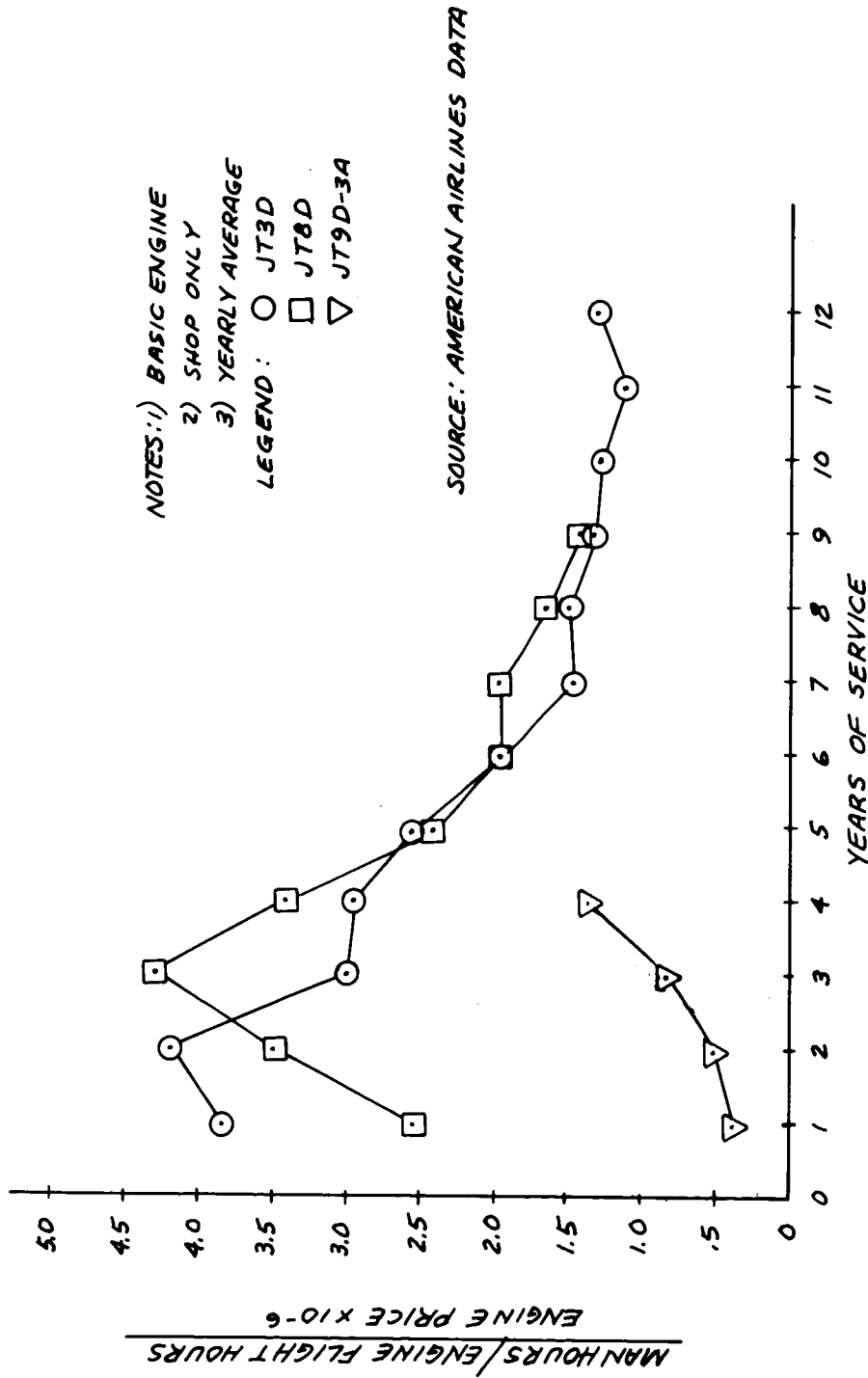


Figure III-10 Manhours Per Engine Flight Hour Normalized For Engine Price Shows the JT9D at a Substantially Lower Rate Than the JT3D and JT8D

REV. 4-3-74

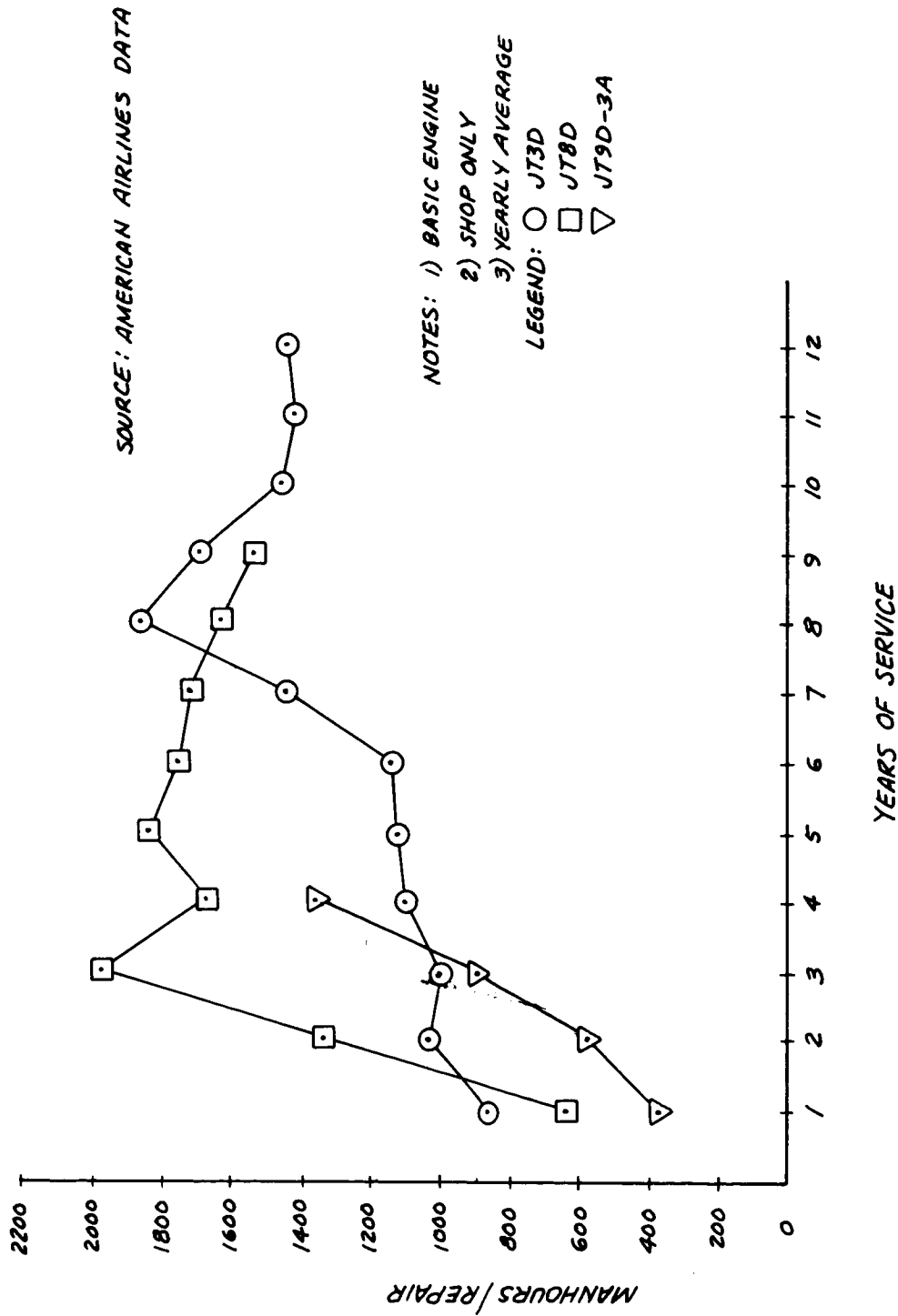


Figure III-11 Manhours Per Repair Increase to Mature Level

REV-4-3-74

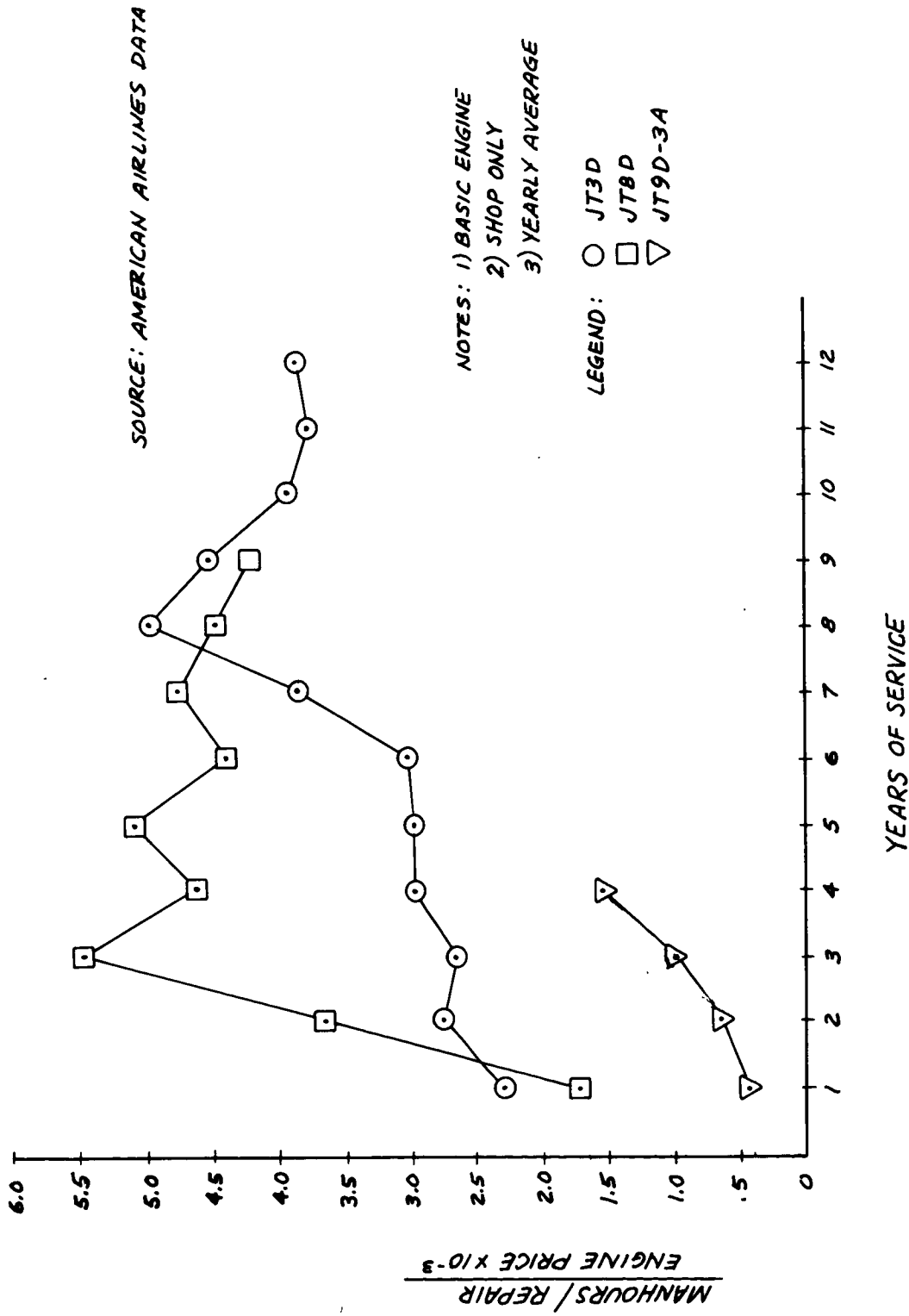


Figure III-12 When Normalized For Engine Price, the JT9D Exhibits Significantly Lower Manhours Per Repair

REV. 4-3-74

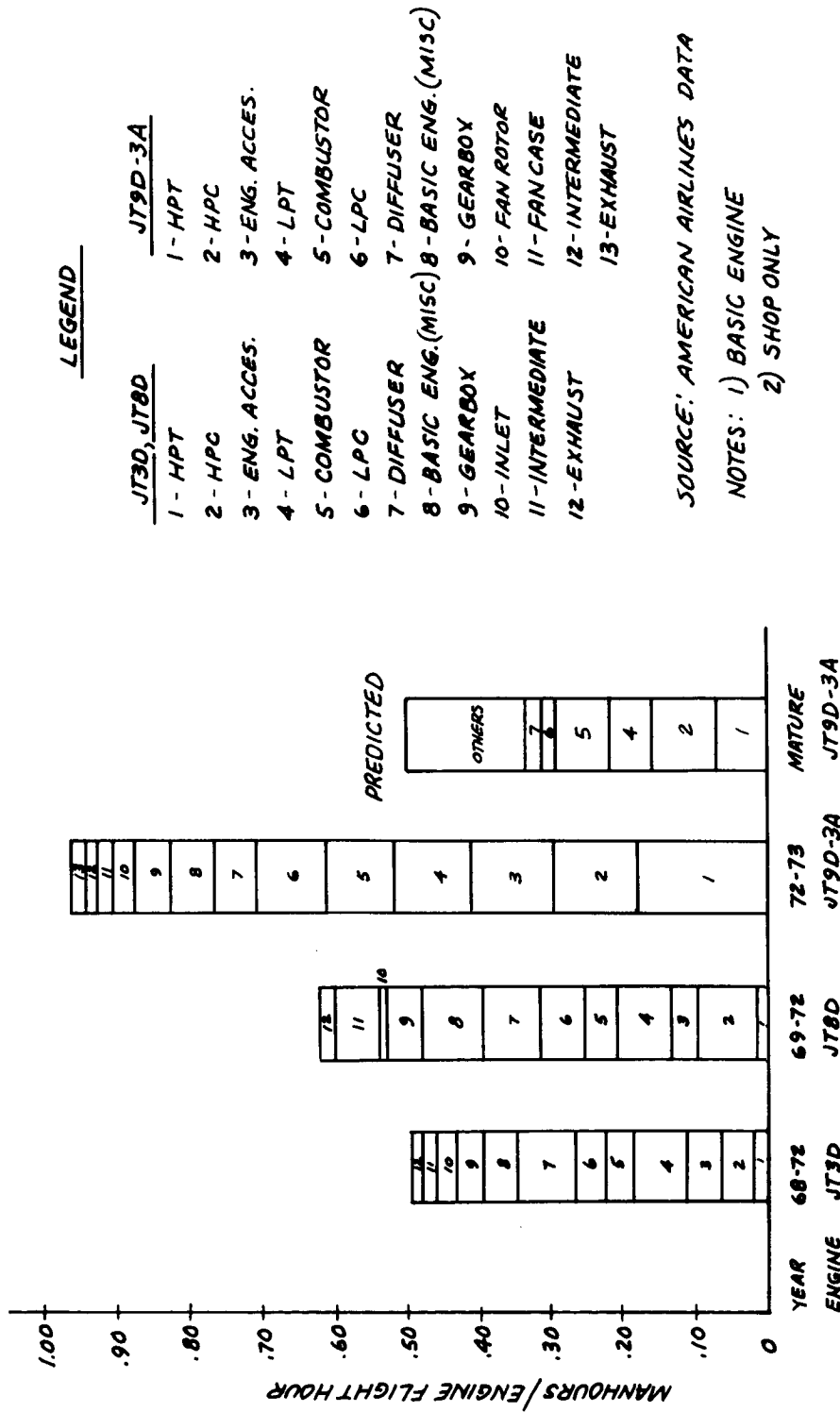


Figure III-13 Contribution of Engine Sections to Total Manhours Per Engine Flight Hour

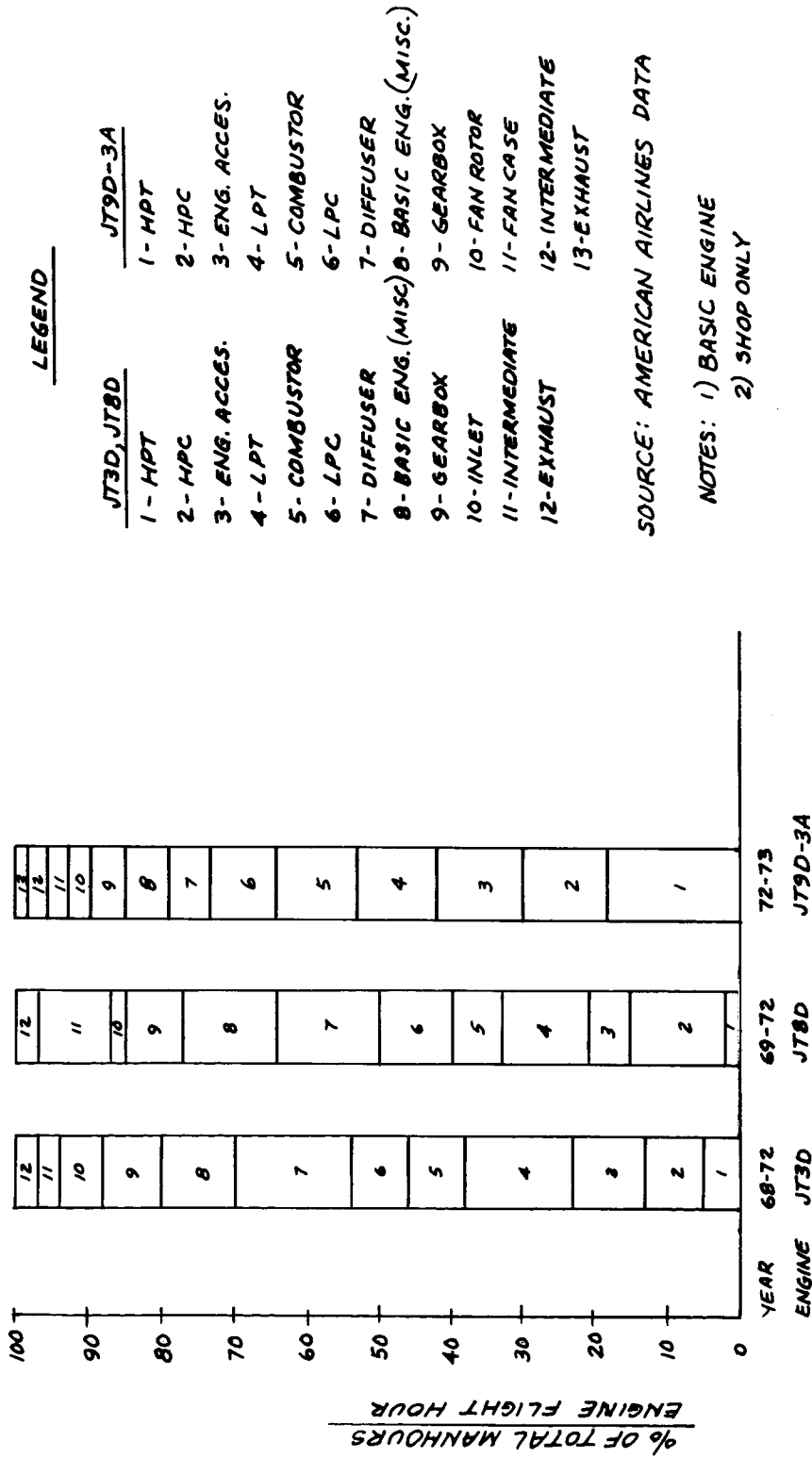


Figure III-14 Relative Contribution of Engine Sections to Manhours/Engine Flight Hour

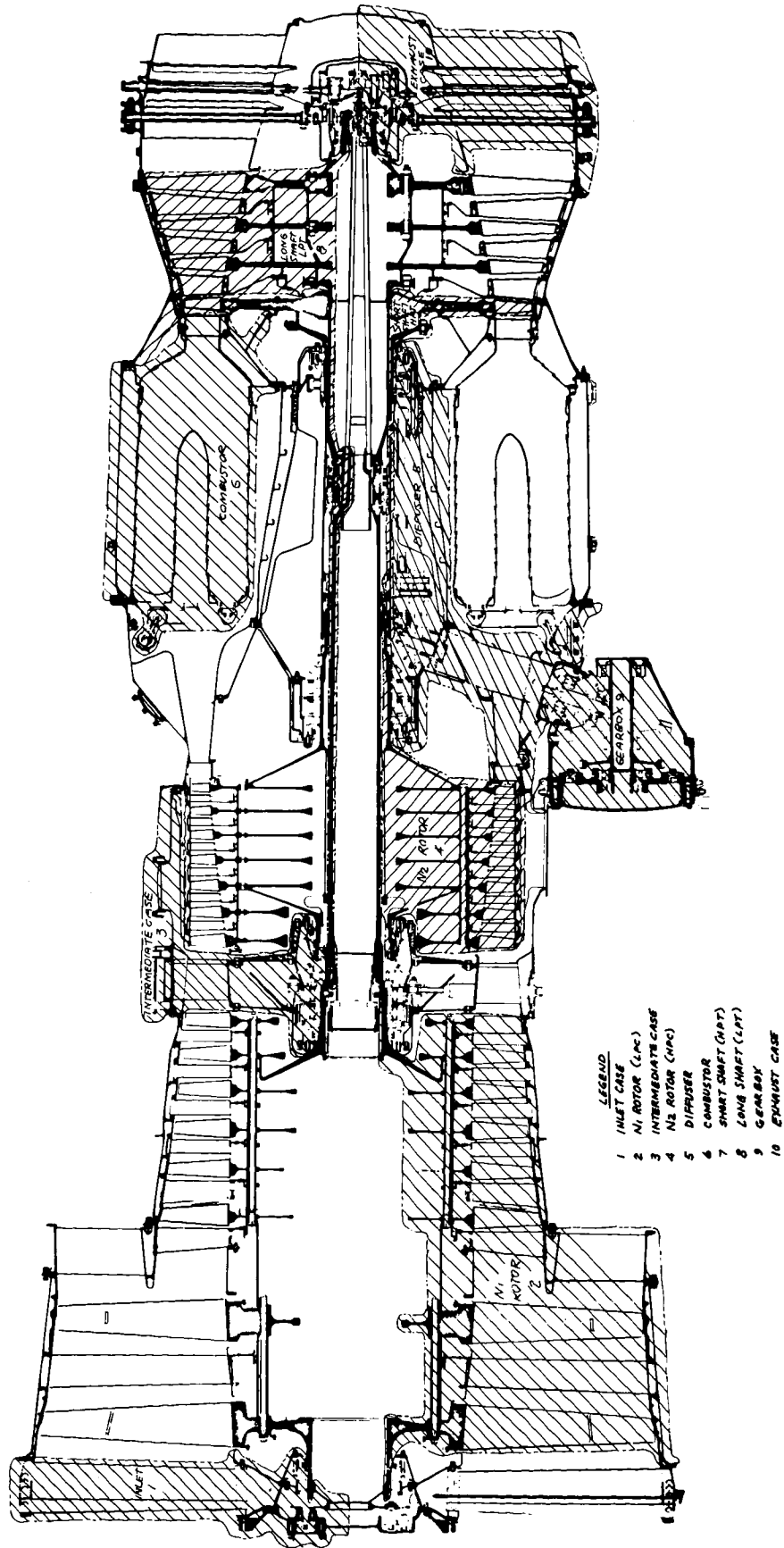


Figure III-15 JT3D Engine Cross Section With Engine Sections Identified

- LEGEND
- | | |
|------------------------------|---------------------|
| 1 INLET CASE | 6 COMBUSTOR |
| 2 N ₁ ROTOR (LPC) | 7 SHORT SHAFT (HPT) |
| 3 INTERMEDIATE CASE | 8 LONG SHAFT (LPT) |
| 4 N ₂ ROTOR (HPC) | 9 GEAR BOX |
| 5 DIFFUSER | 10 EXHAUST CASE |

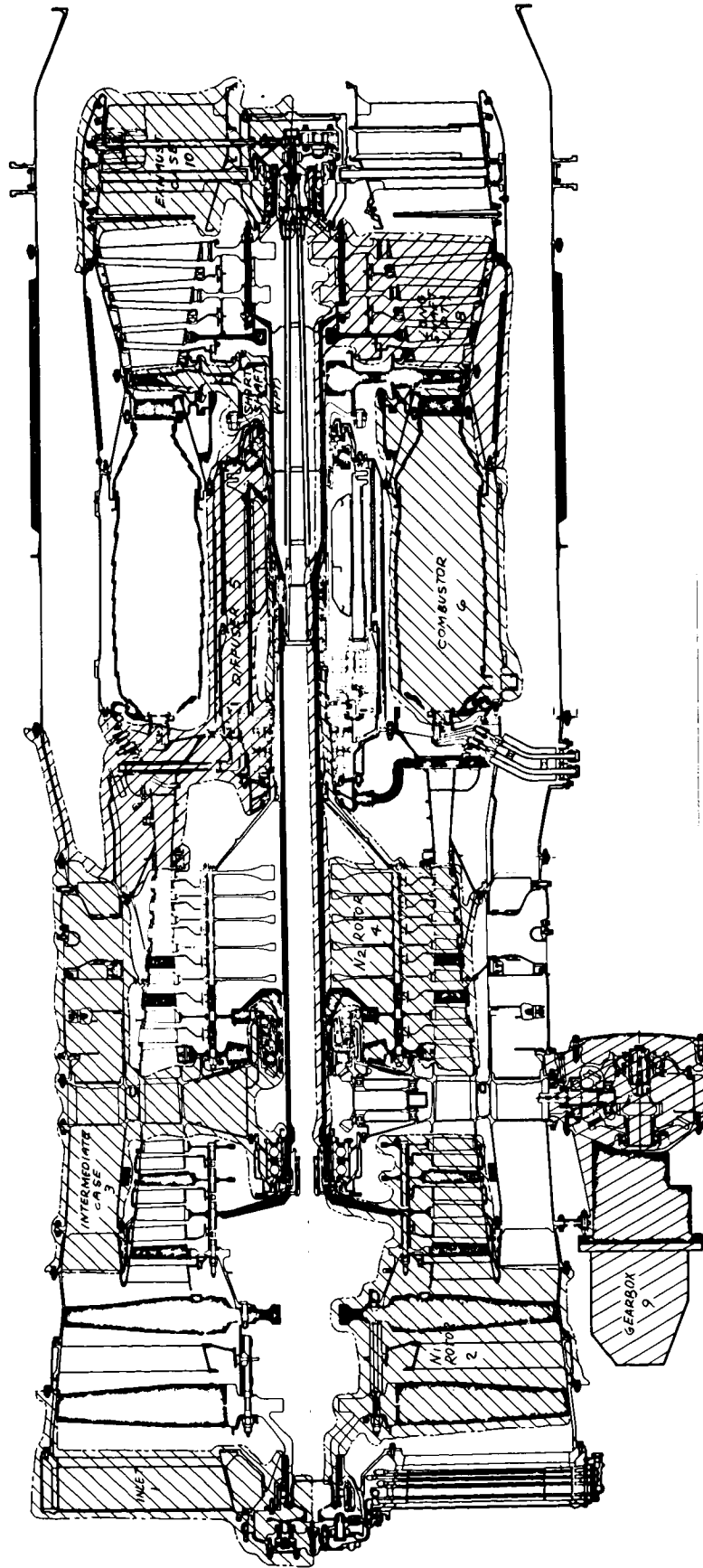


Figure III-16 JT8D Engine Cross Section With Engine Sections Identified

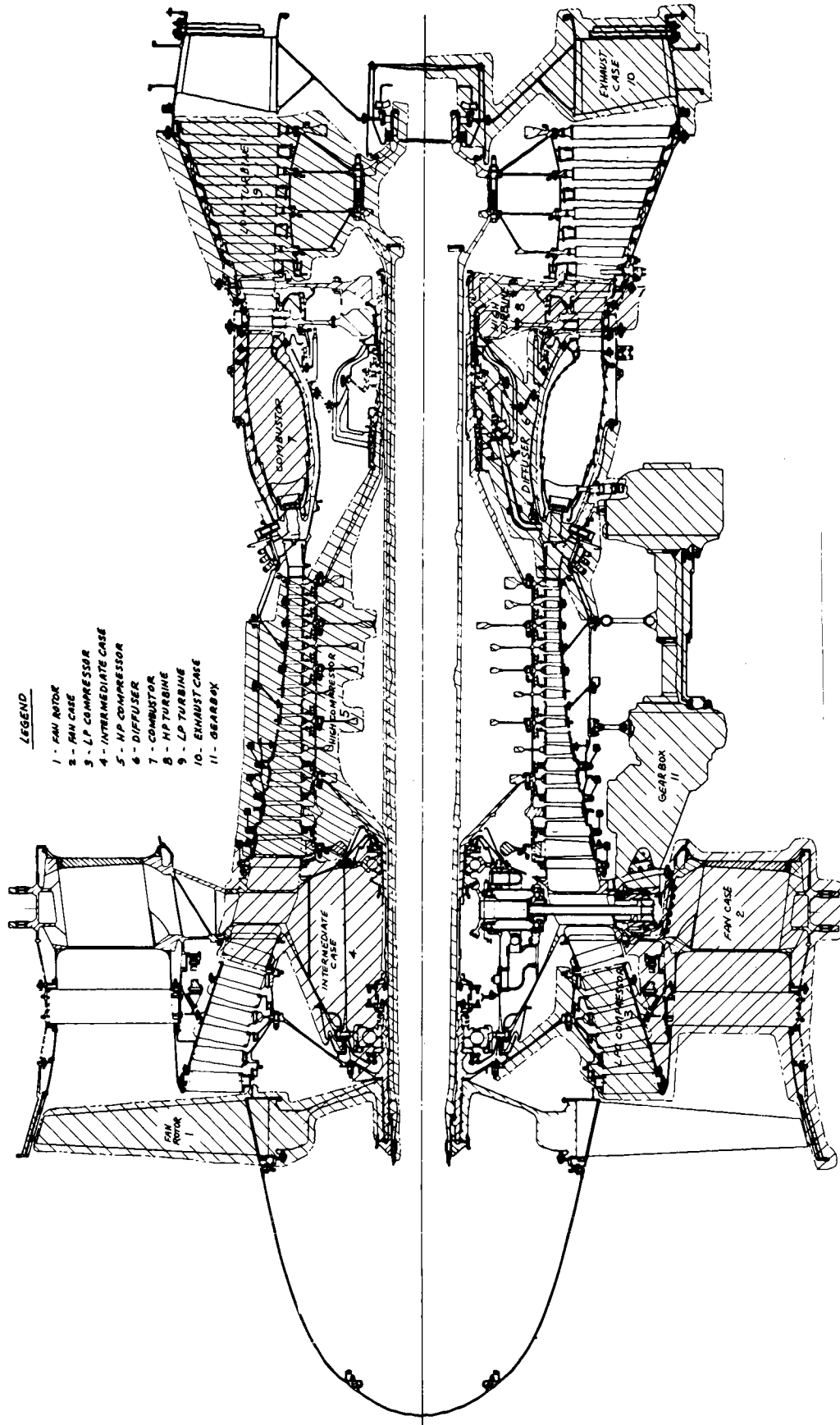


Figure III-17 JT9D Engine Cross Section With Engine Sections Identified

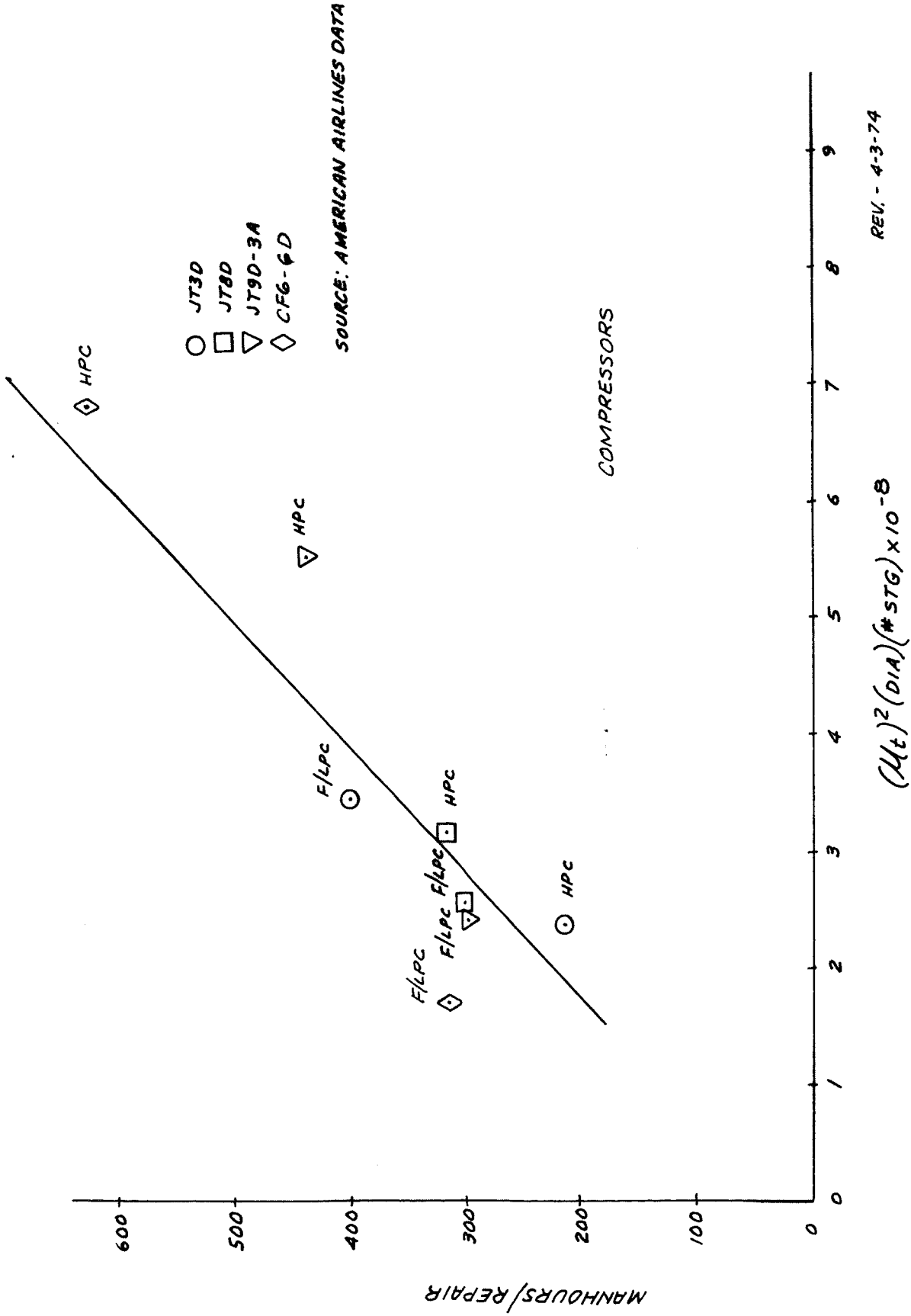


Figure III-18 Compressor Manhours Per Repair Increase With Increasing Tip Speed, Size and Complexity

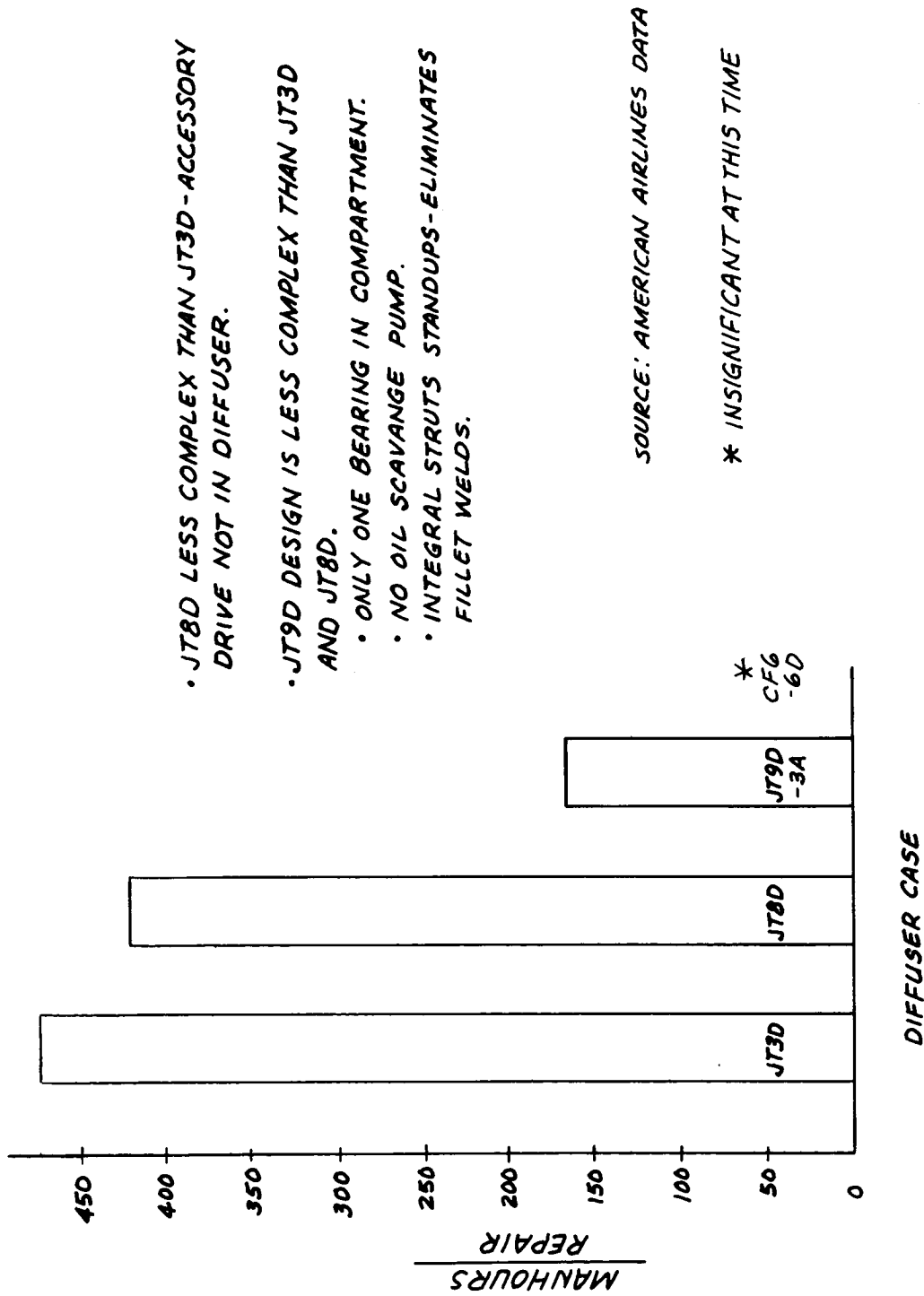


Figure III-19 Design and Construction Techniques Have Significant Impact on Manhours Per Repair for the Diffuser Case REV. 4-2-74

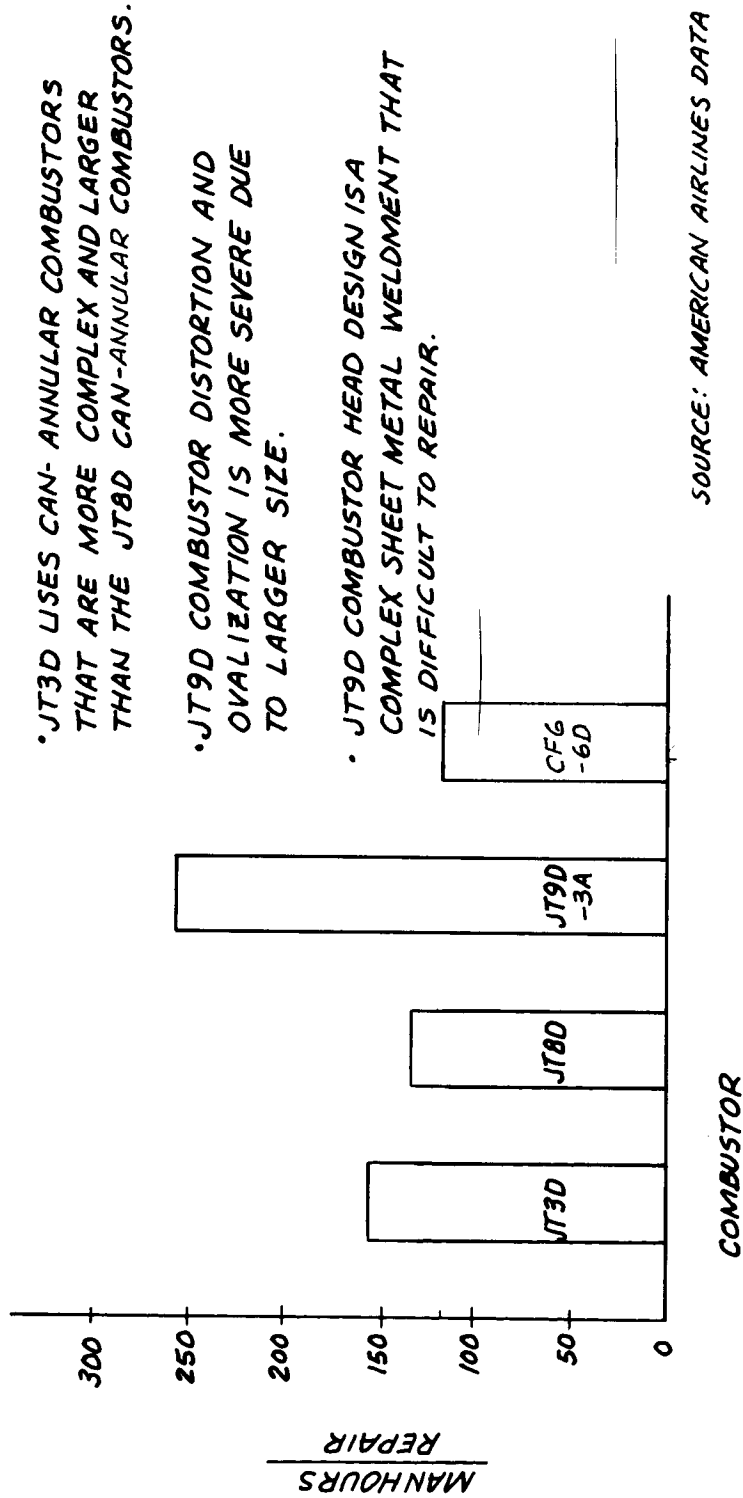


Figure III- 19A Combustor Manhours Per Repair Increase With Size and Complexity



Figure III-20
Turbine Manhours Per Repair Increase With Increasing Temperature,
Size and Complexity

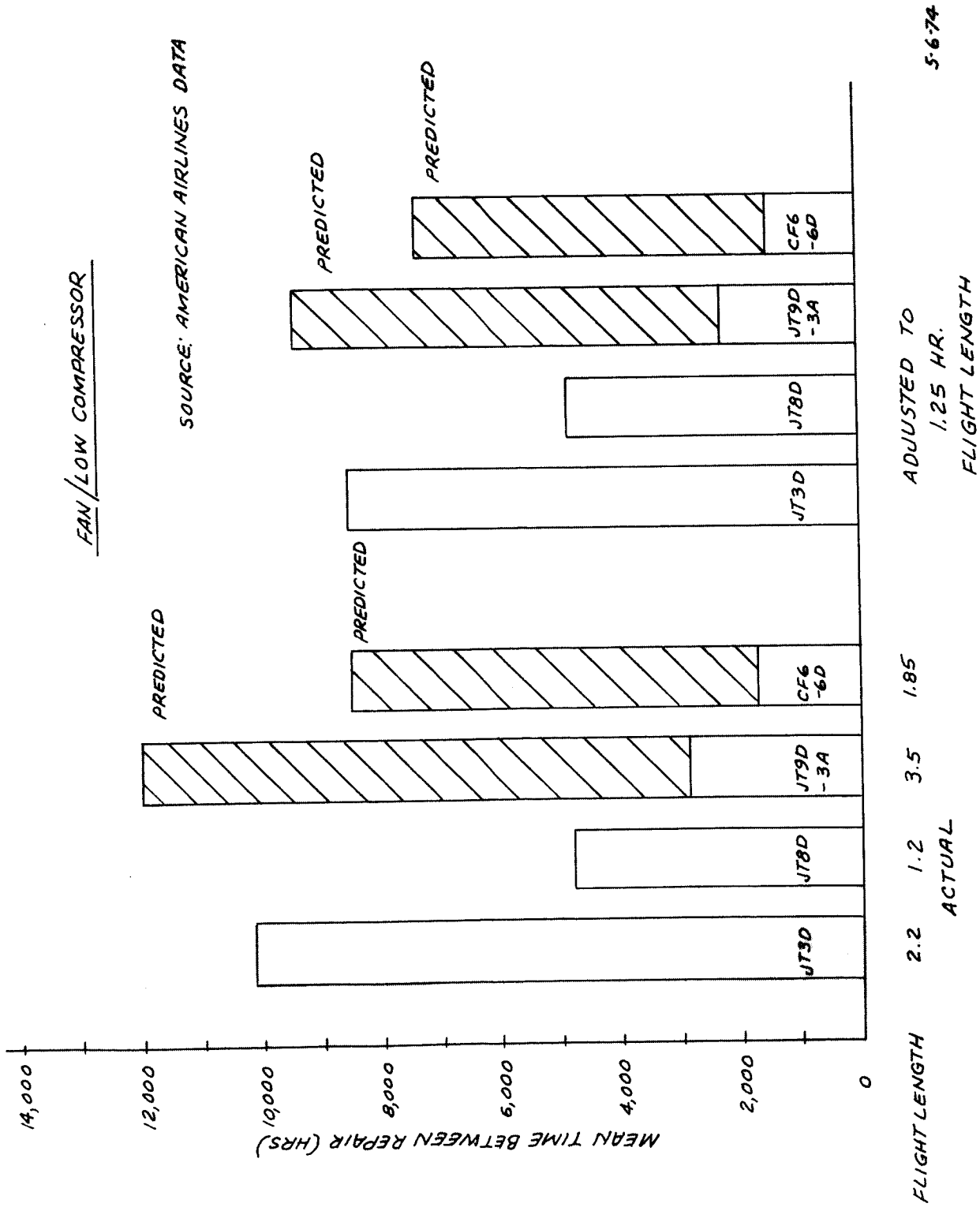


Figure III-21 Fan/Low Compressor Mean Time Between Repair Adjusted For Flight Length

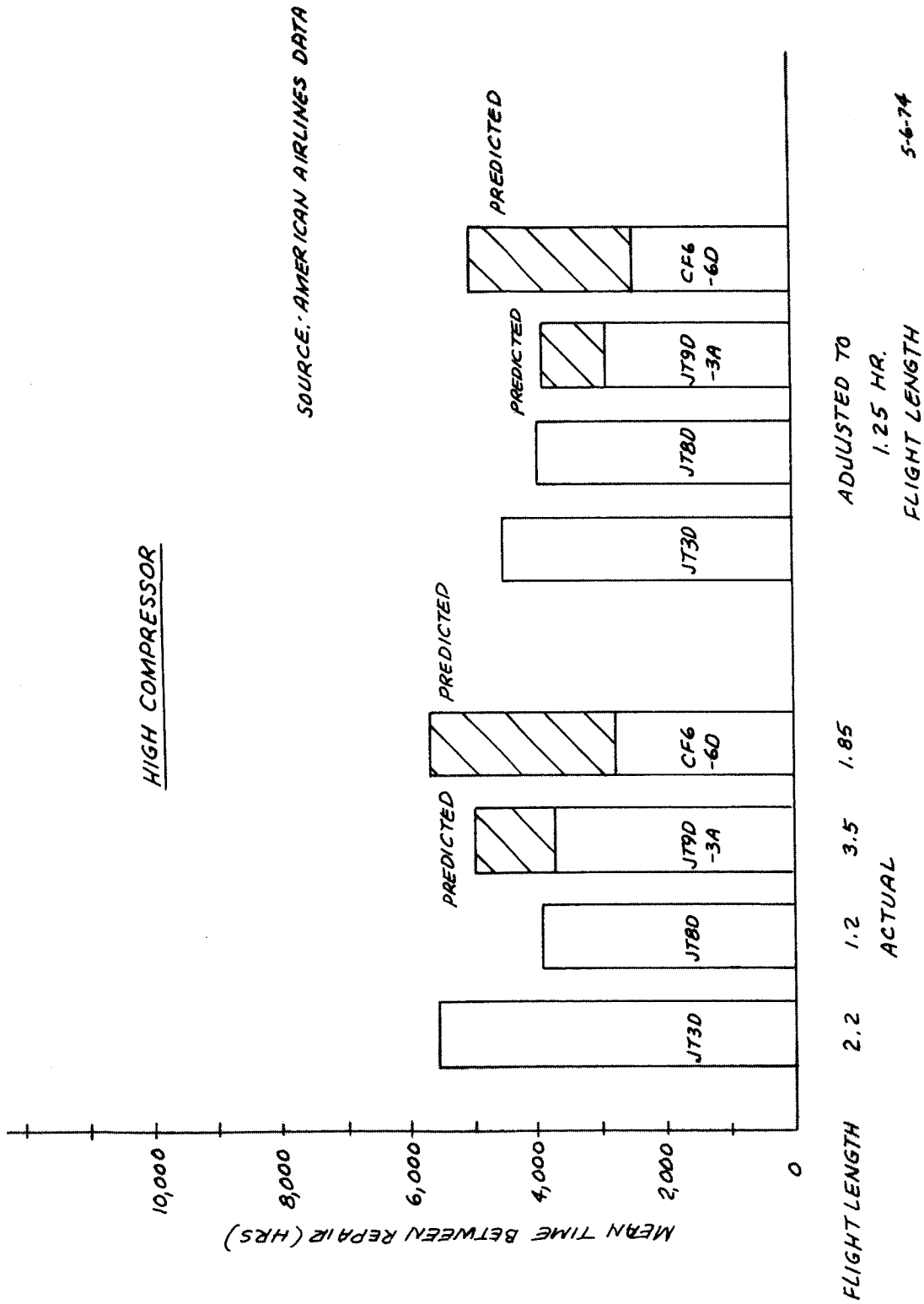


Figure III-22 High Compressor Mean Time Between Repair Adjusted For Flight Length

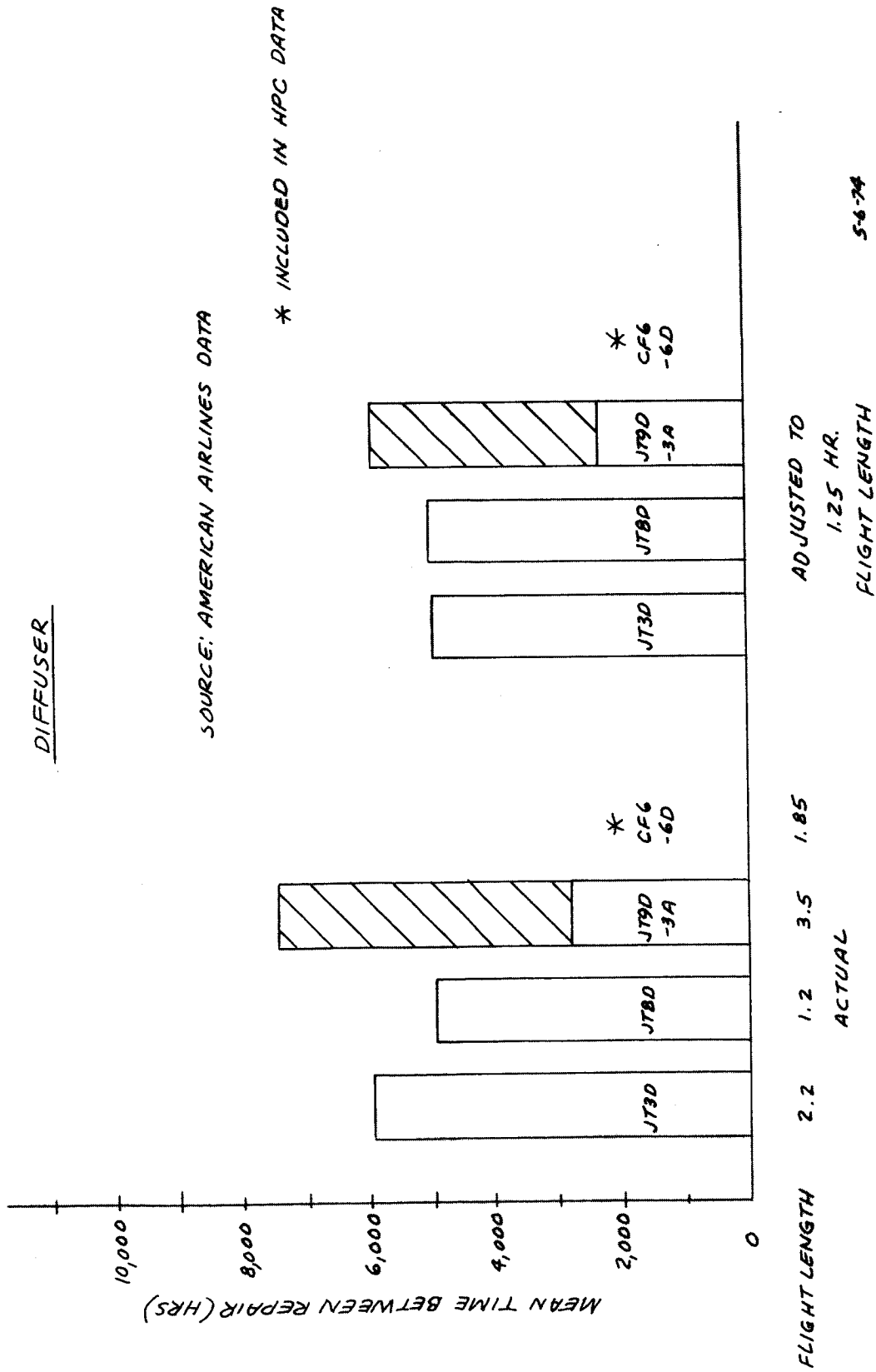


Figure III-23 Mean Time Between Repair of the Diffuser Case is Close for all Three Engines on an Adjusted Basis

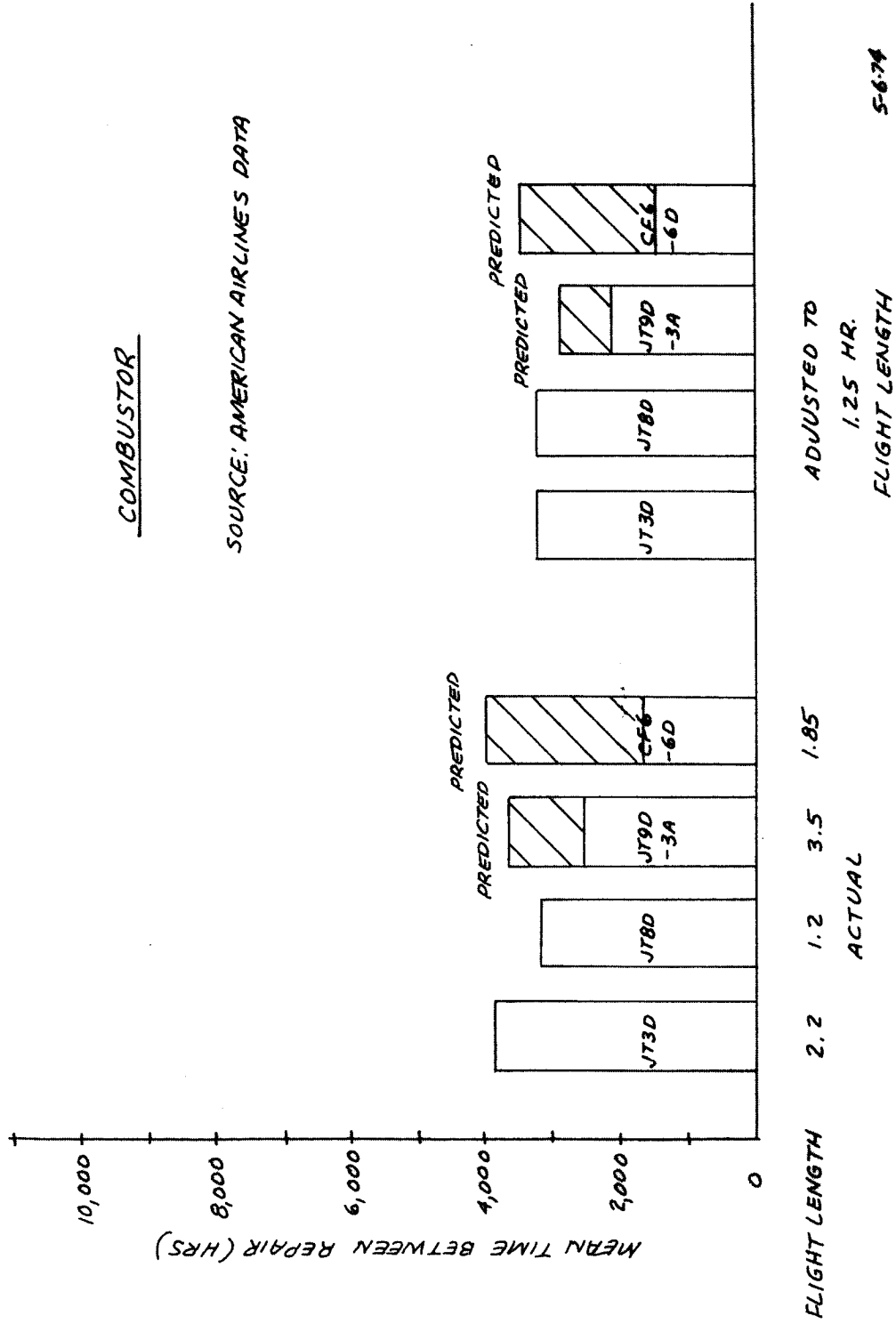


Figure III-24 Combustor Mean Time Between Repair Adjusted For Flight Length

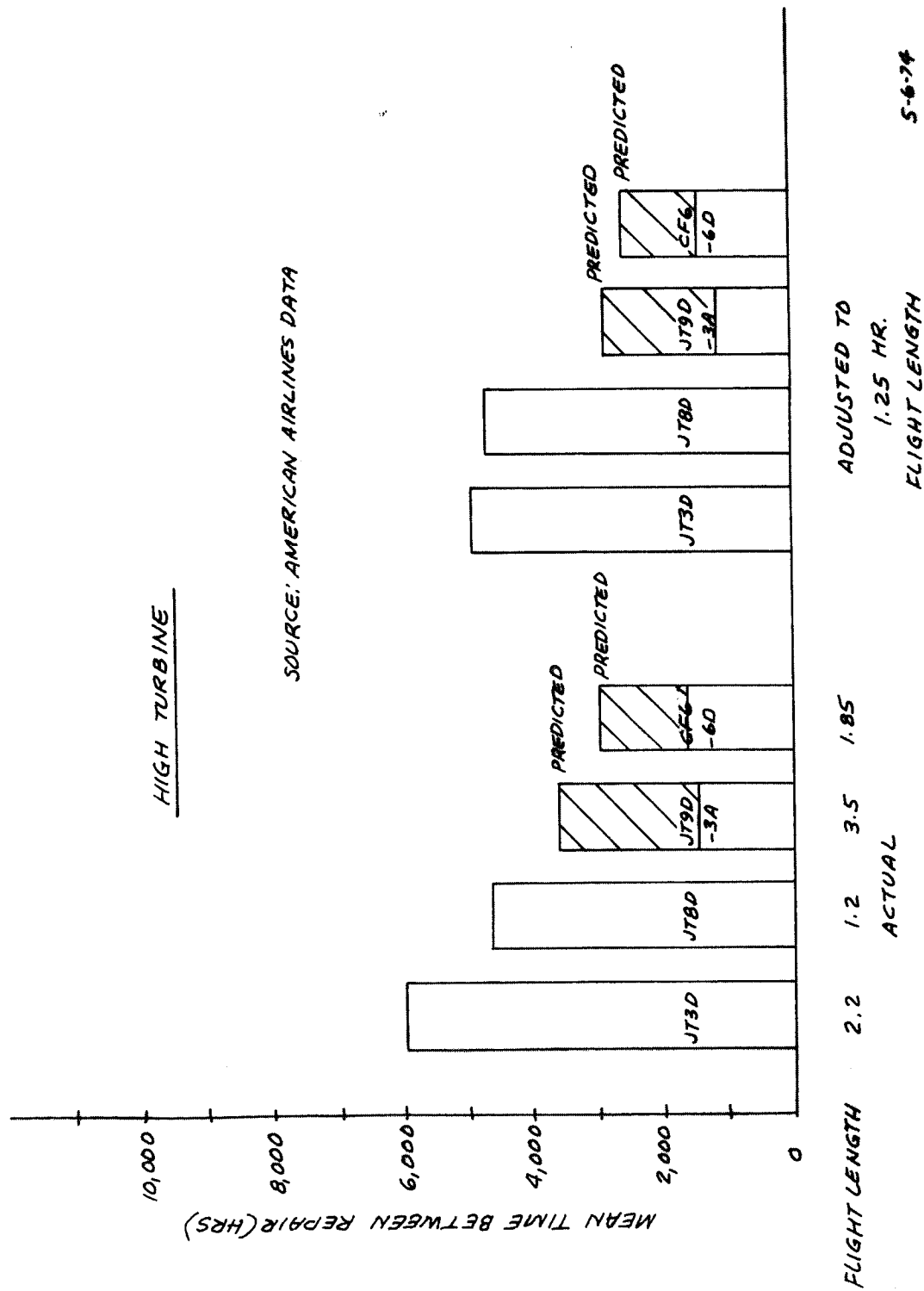


Figure III-25 High Turbine Mean Time Between Repair Adjusted For Flight Length

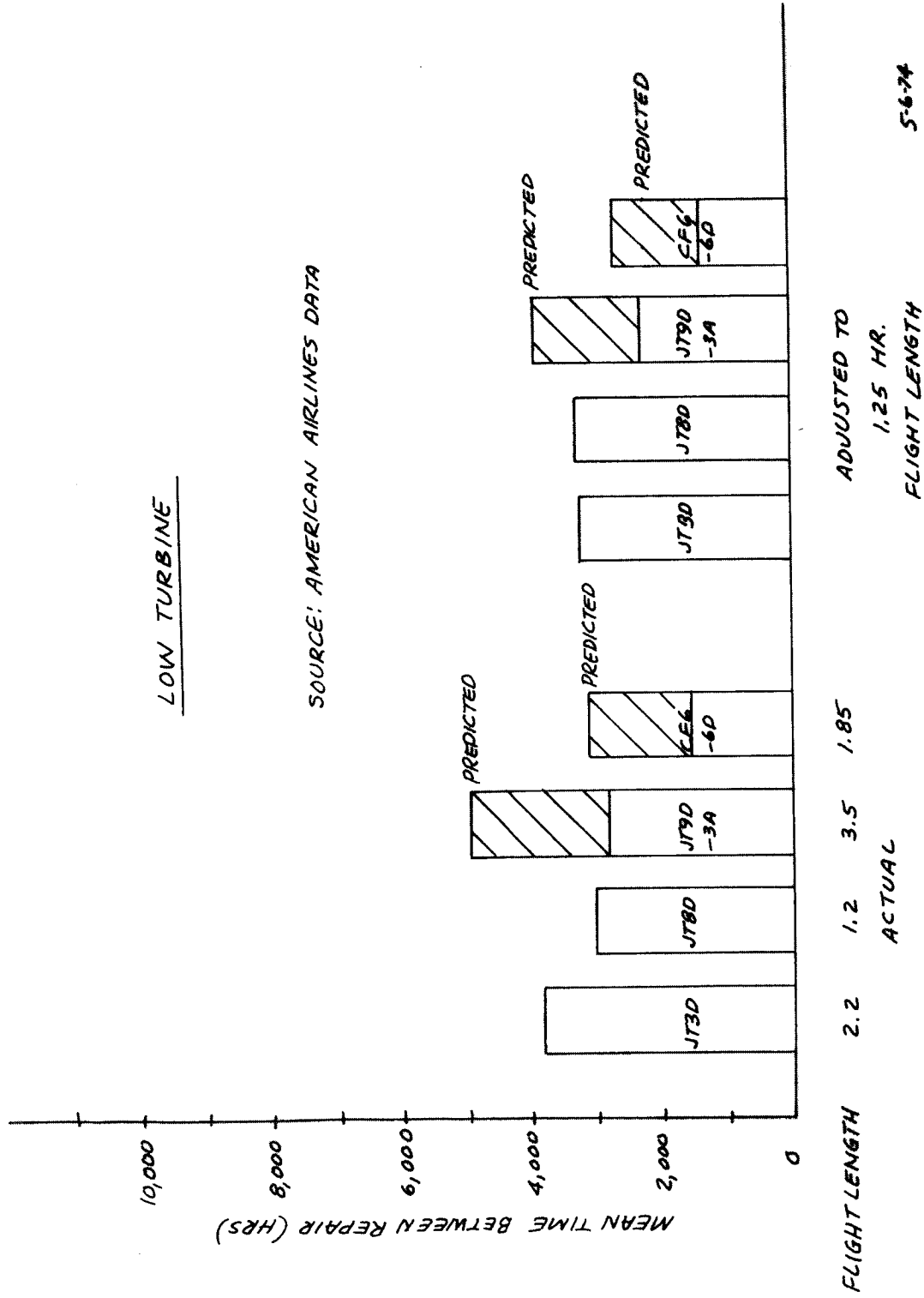


Figure III-26 Low Turbine Mean Time Between Repair Adjusted For Flight Length

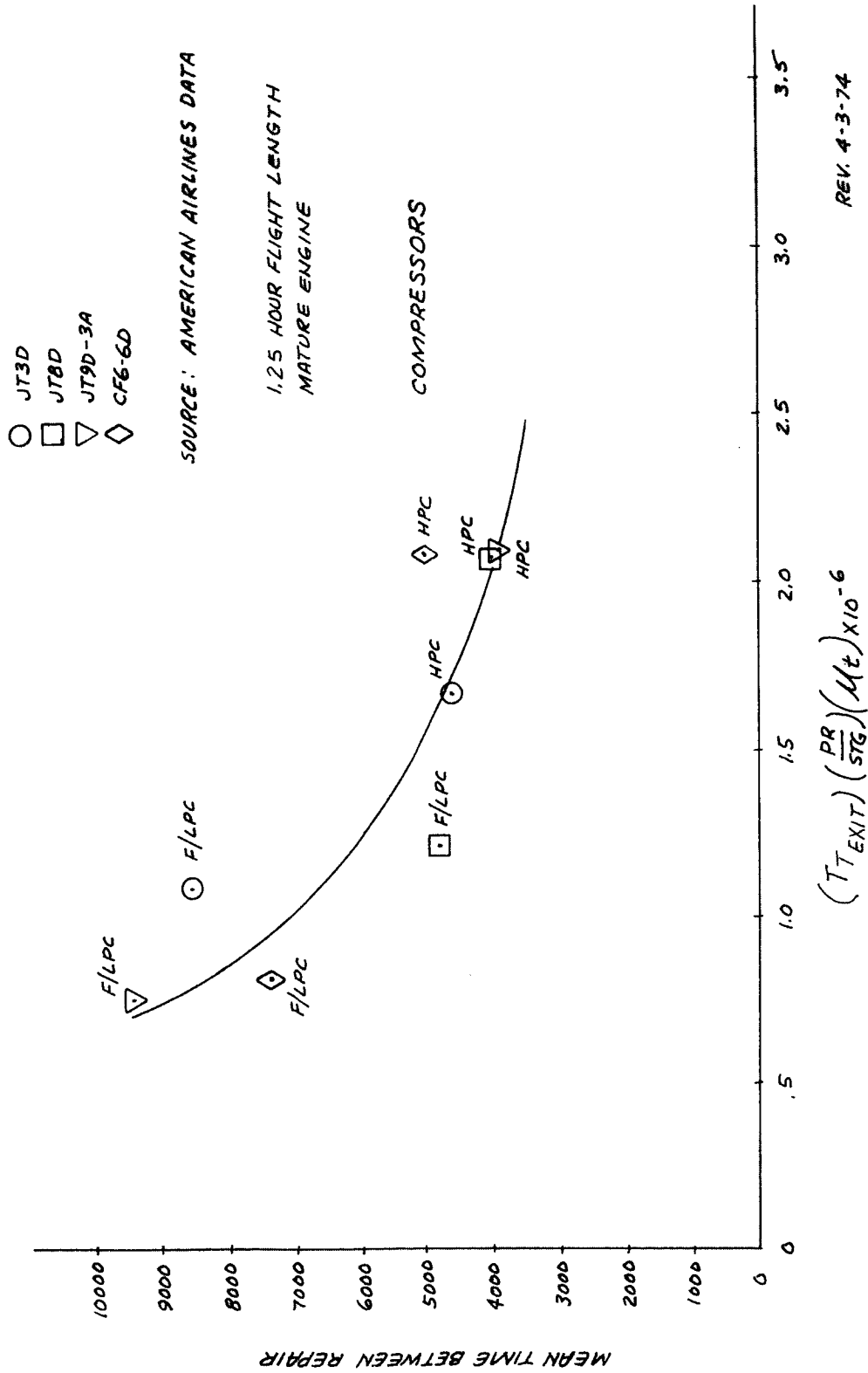
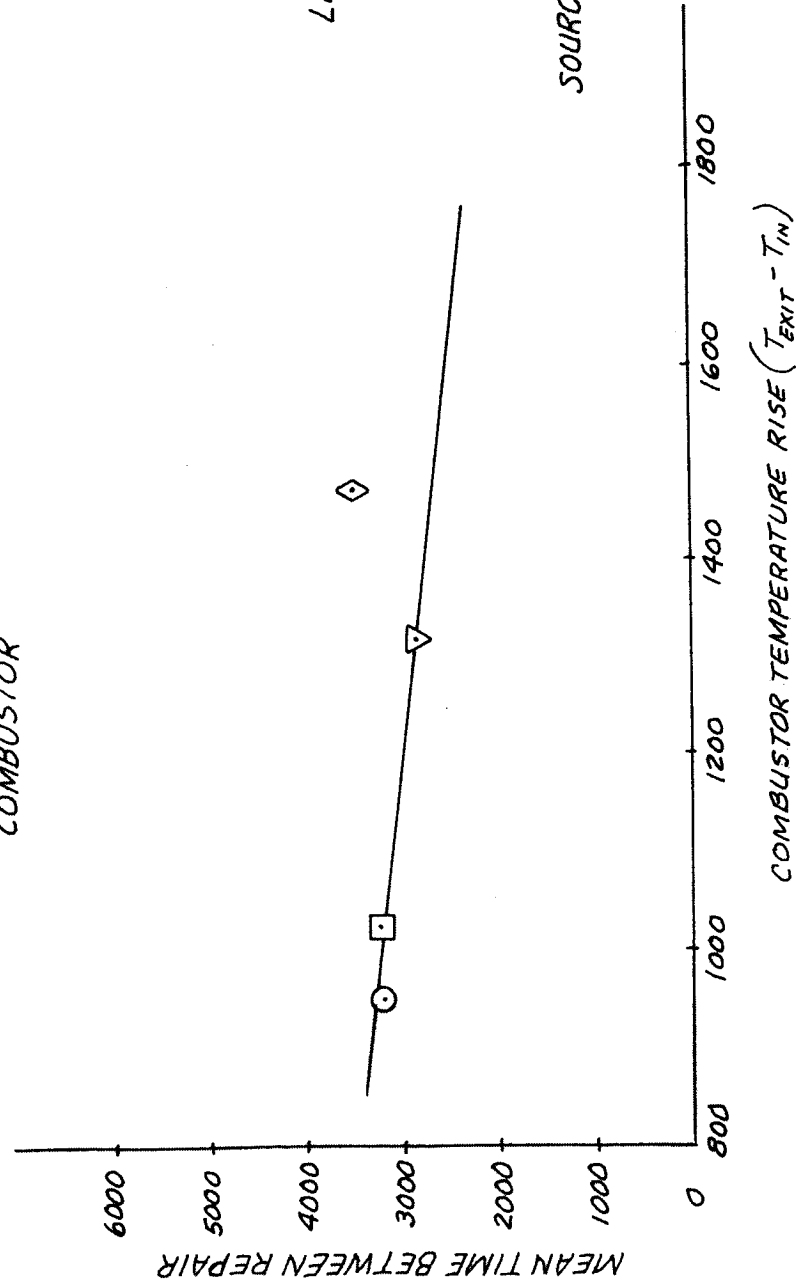


Figure III-27 Compressor Mean Time Between Repair Decreases With Increasing Compressor Exit Temperature, Pressure Ratio Per Stage, and Tip Speed

1.25 HOUR FLIGHT LENGTH
MATURE ENGINE

COMBUSTOR



SOURCE: AMERICAN AIRLINES DATA

Figure III-28 Combustor Mean Time Between Repair Decreases With Increasing Combustor Temperature Rise

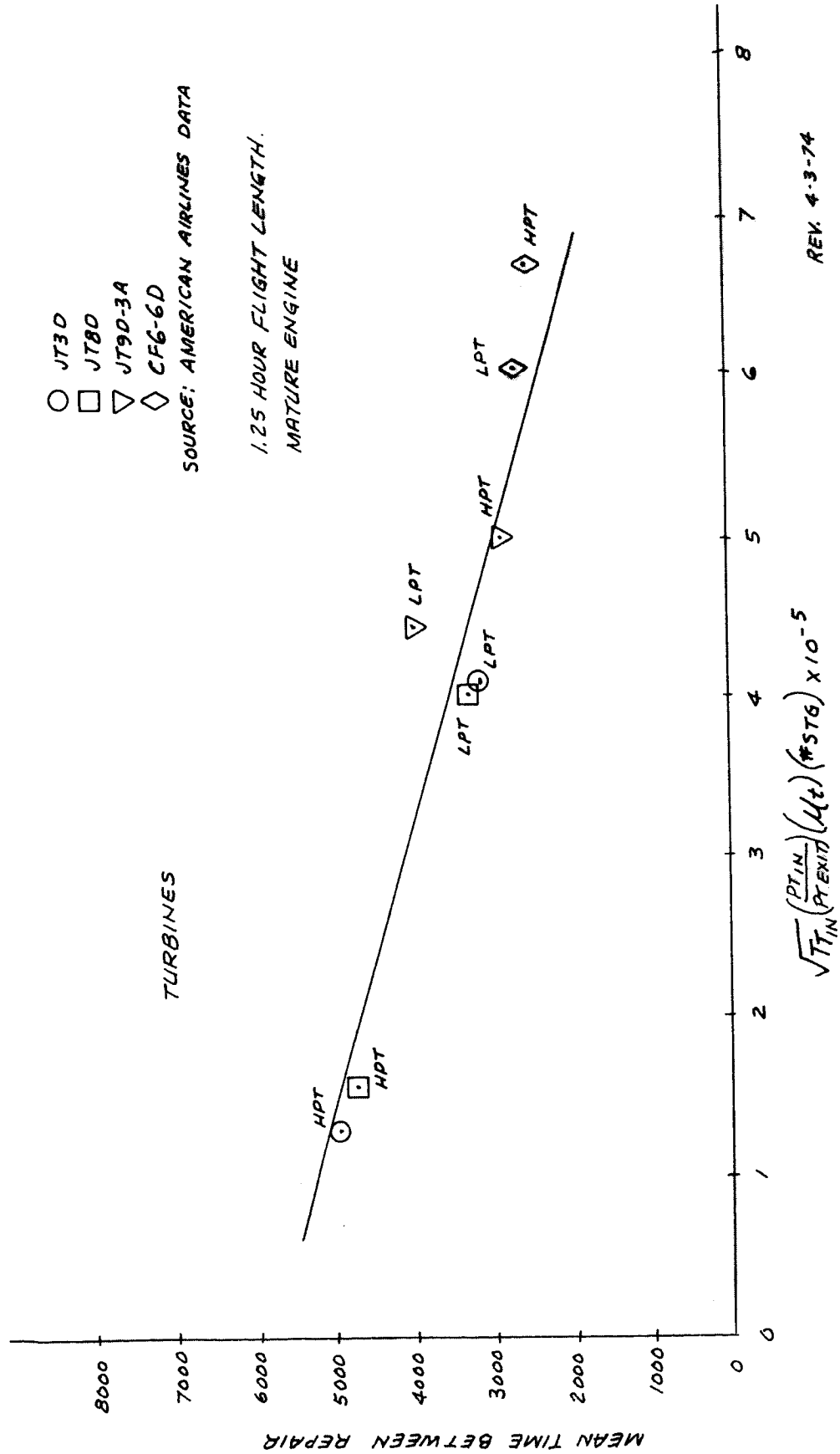


Figure III-29 Turbine Mean Time Between Repair Decreases With Increasing Turbine Temperature, Expansion Ratio, Tip Speed and Number of Stages

MODULE	MTBR		AVERAGE FLIGHT LENGTH (HRS)
	JT3D	JT8D	
FAN/LPC	10,230	4800	2.2
HPC	5,550	3960	
DIFFUSER	5,930	5000	1.2
COMBUSTOR	3,820	3190	
HPT	5,930	4700	MATURE ENGINE
LPT	3,820	3200	
MEAN TIME BETWEEN ENGINE REMOVAL (MTBER)	3,195	2646	SOURCE: AMERICAN AIRLINES DATA

NOTES: JT3D 2.2
JT8D 1.2
MATURE ENGINE
SOURCE: AMERICAN AIRLINES DATA

$$\frac{\text{MTBR}}{\text{MINIMUM MODULE MTBR}}$$

$$\frac{\text{JT3D MTBR}}{\text{MIN. MTBR}} = \frac{3195}{3820} = .836$$

$$\frac{\text{JT8D MTBR}}{\text{MIN. MTBR}} = \frac{2646}{3190} = .830$$

Figure III-29A Experience Indicates that Mean Time Between Engine Removal is 83% of the Minimum Module Mean Time Between Repair

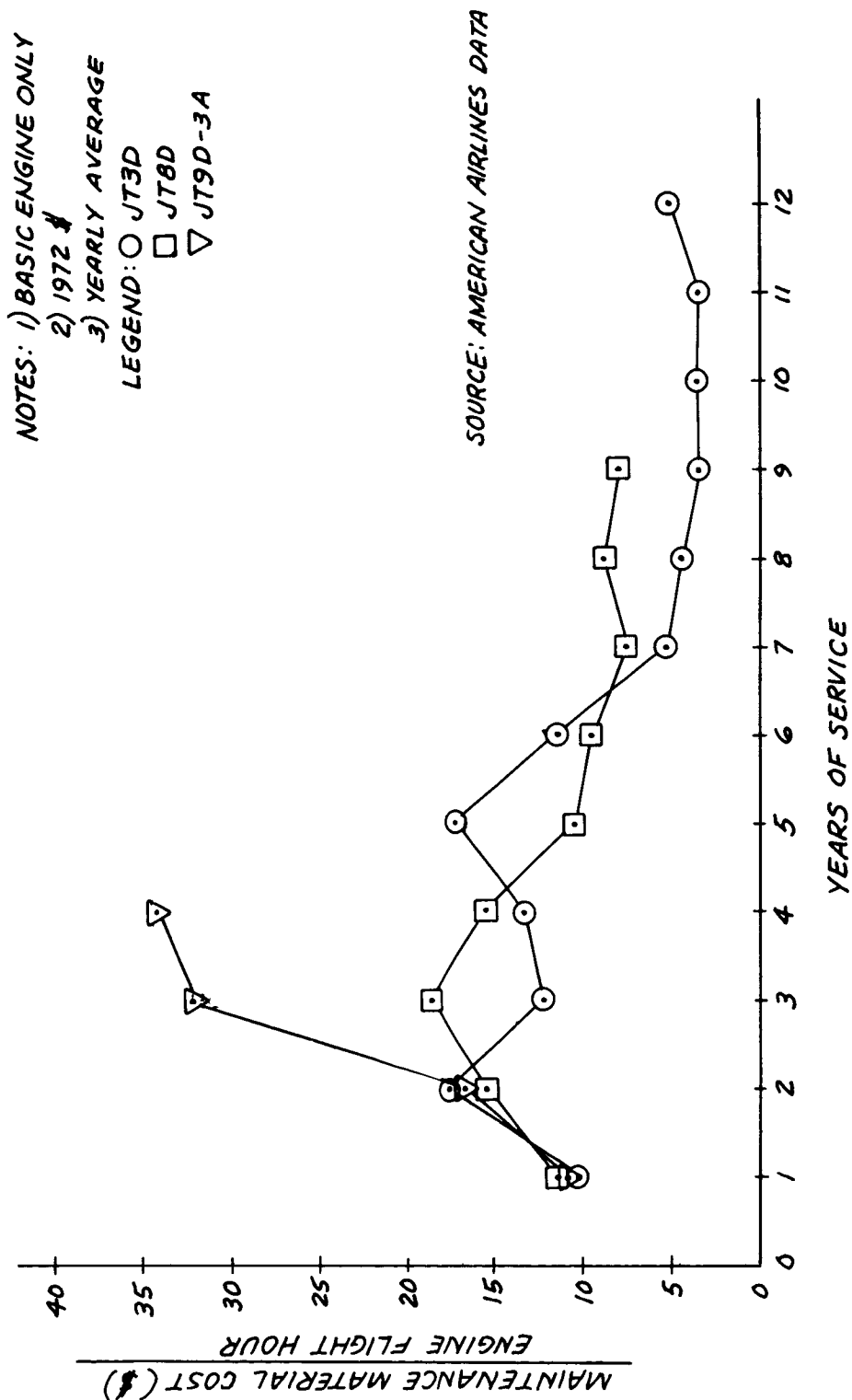


Figure III-30 Maintenance Material Cost Decreases As the Engines Mature

REV. 4-4-74

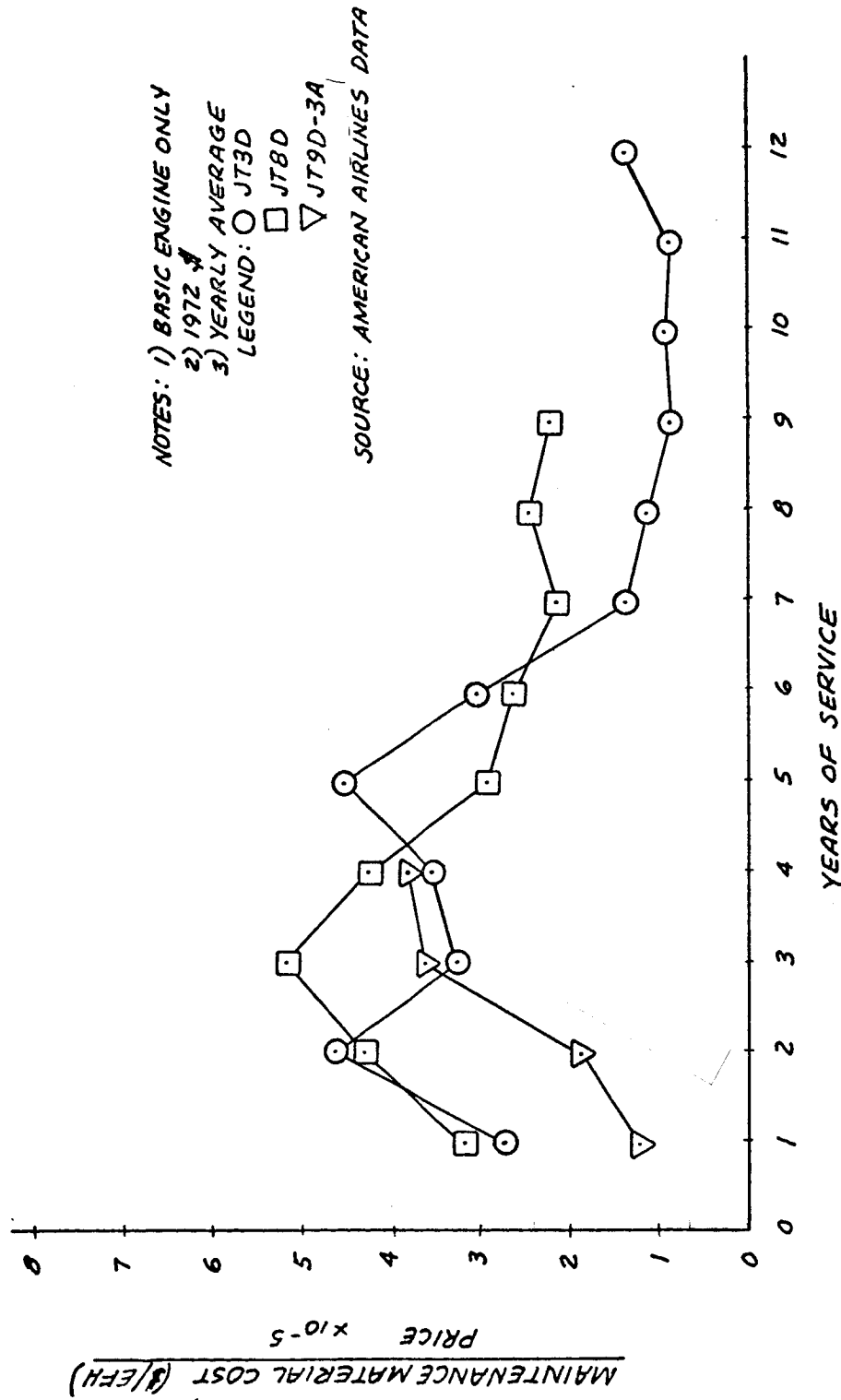


Figure III-31 Maintenance Material Cost Normalized for Eng. Price Shows the JT9D at a Lower Rate Than the JT3D and JT8D

REV. 4-10-74

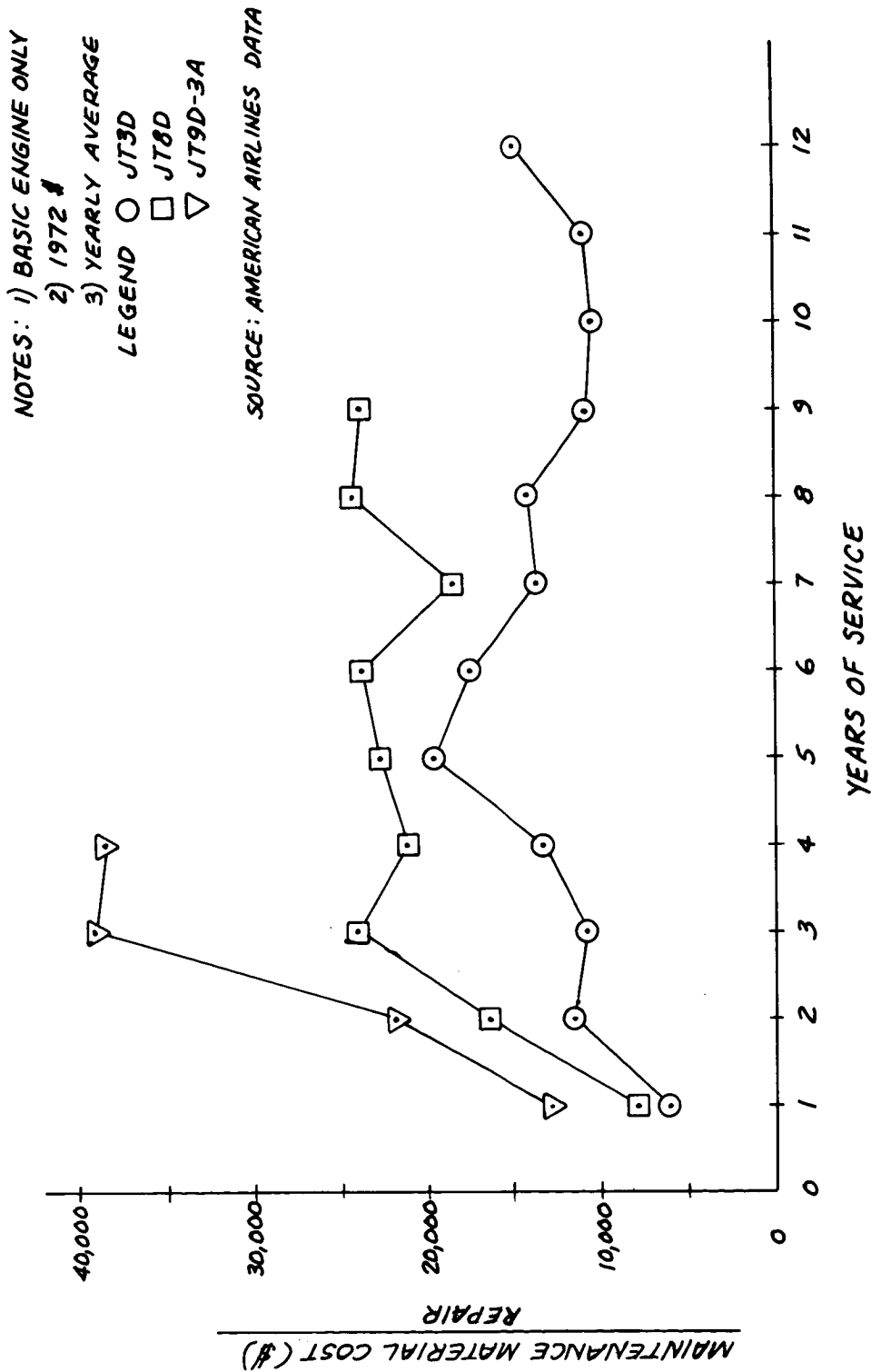


Figure III-32 Maintenance Material Cost per Repair Reaches a Mature Value Quickly

REV. 4-10-74

NOTES: 1) BASIC ENGINE ONLY
 2) 1972 \$
 3) YEARLY AVERAGE
 LEGEND ○ JT3D
 □ JT8D
 ▽ JT9D-3A

SOURCE: AMERICAN AIRLINES DATA

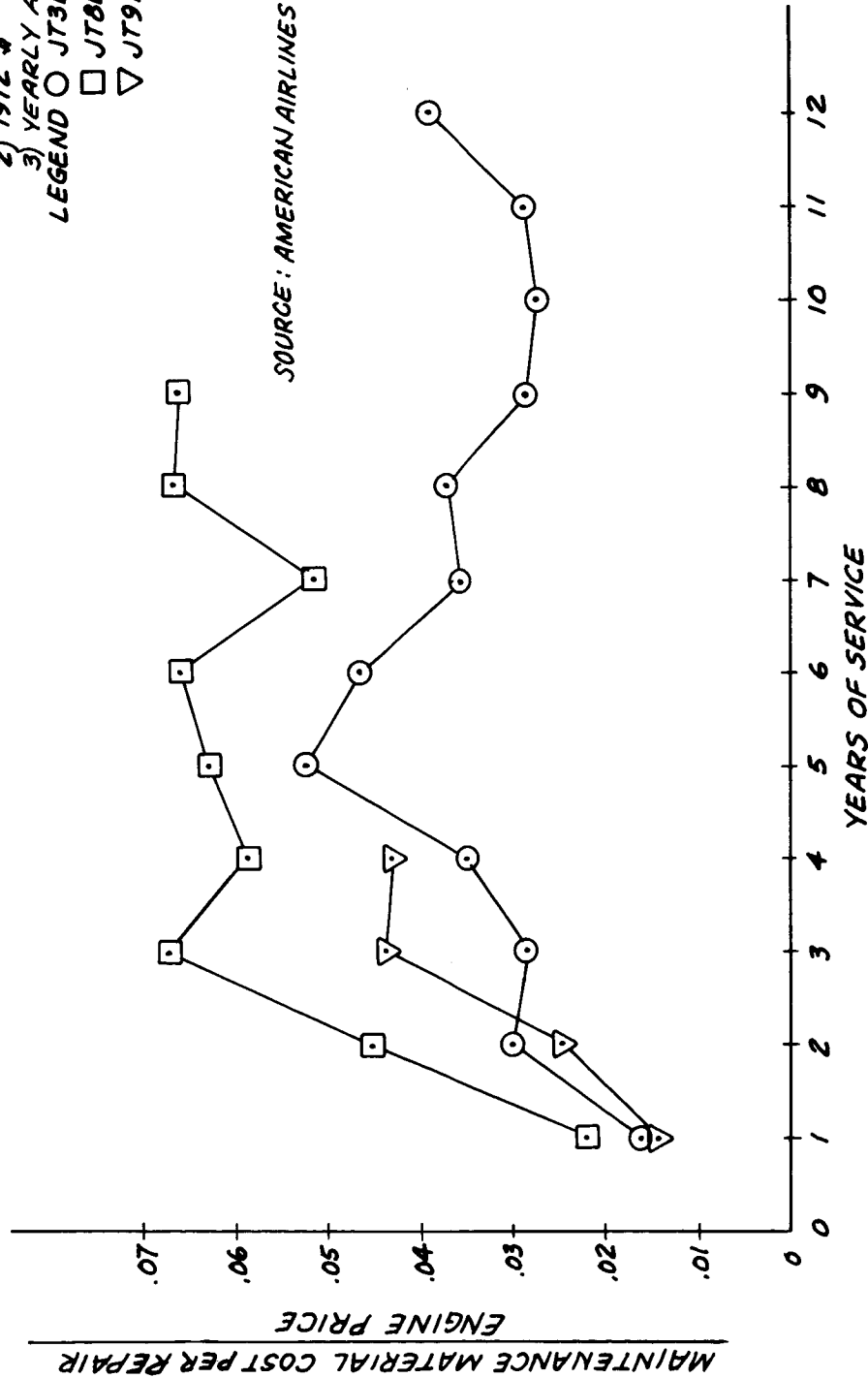


Figure III-33 Maintenance Material Cost per Repair Spread is Reduced by Normalizing for Engine Price

REV. 4-9-74

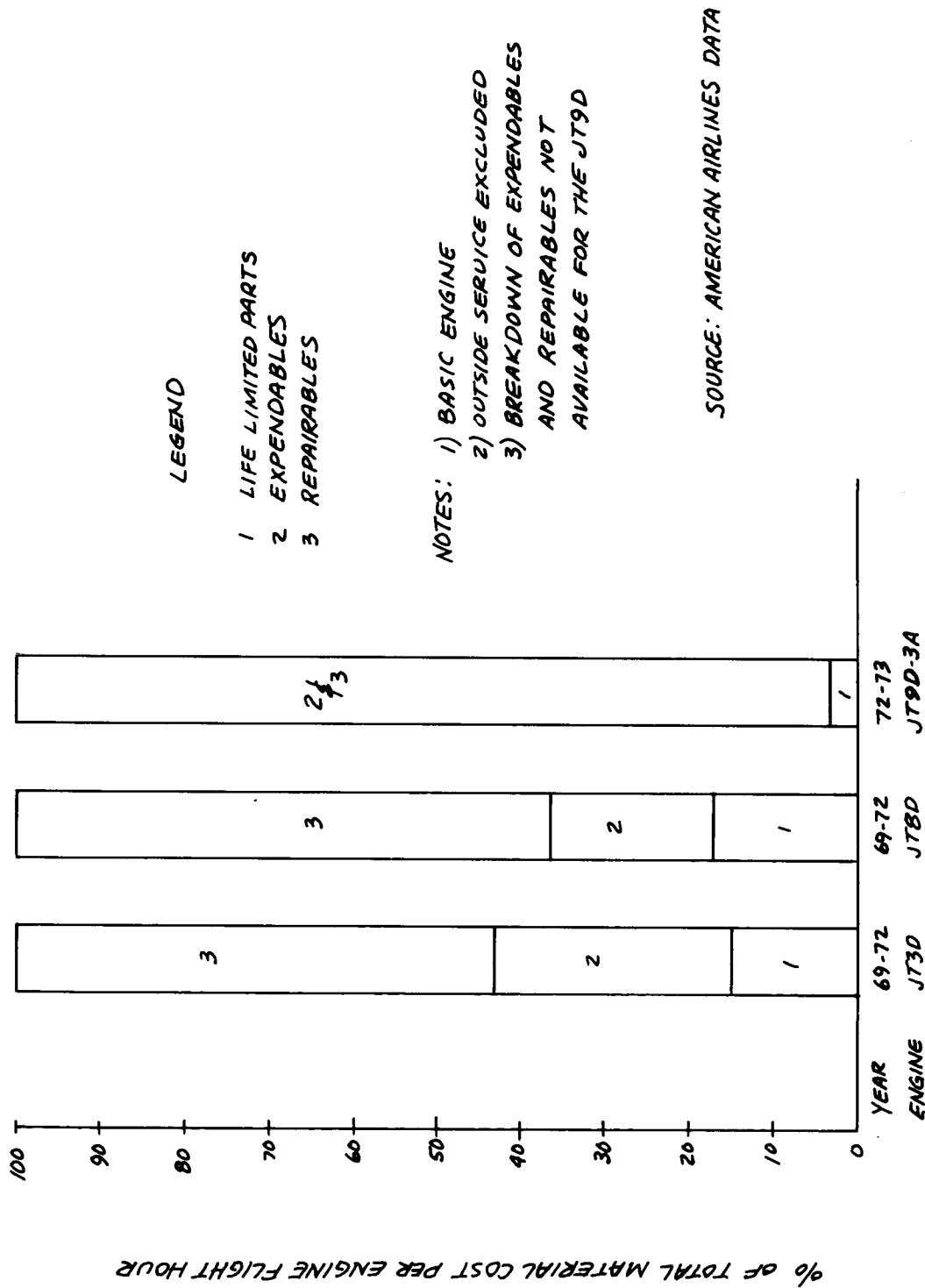


Figure III-34 Contribution of Repairs, Expendables and Life Limited Parts to Maintenance Material Cost

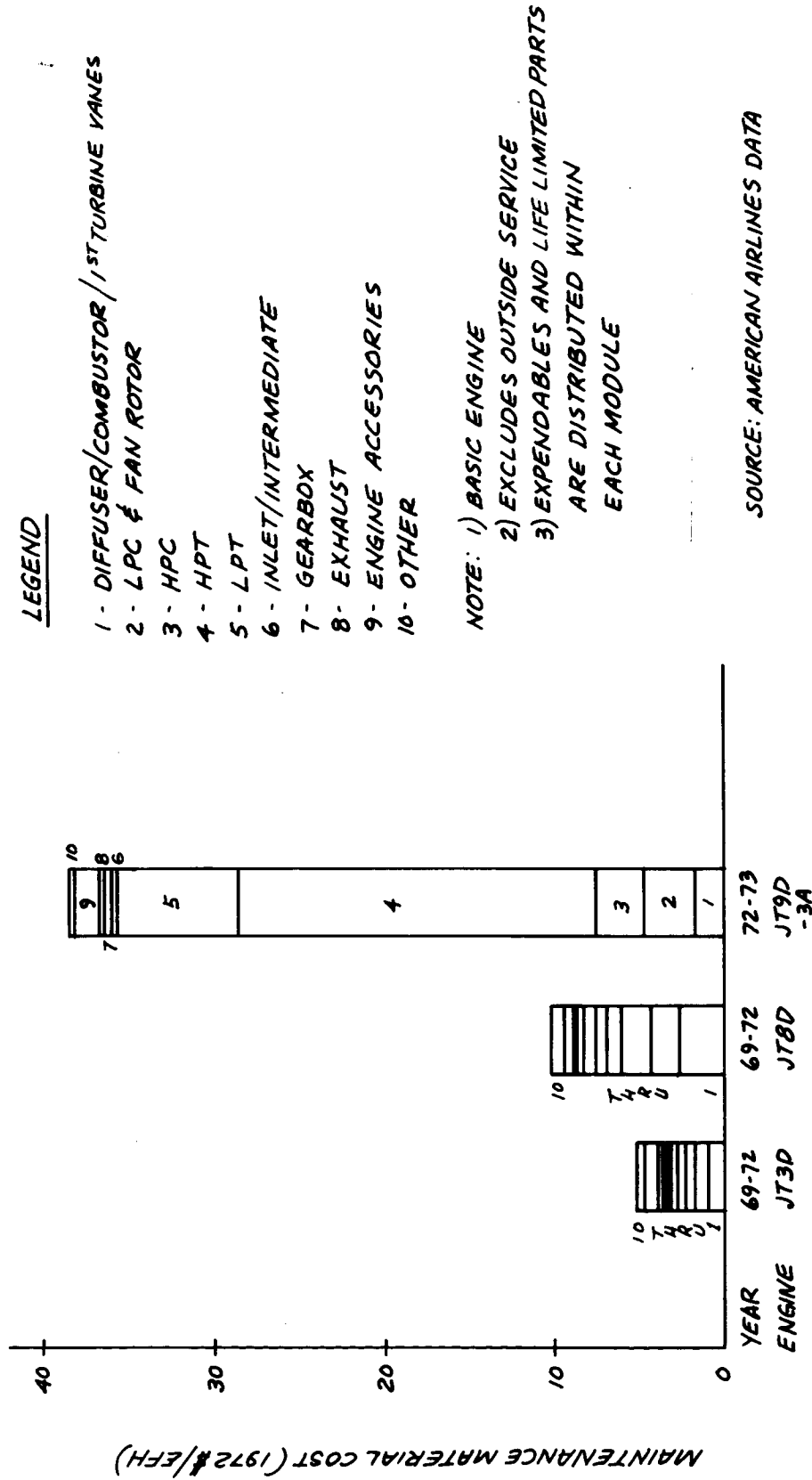


Figure III-35 Contribution of Engine Module Sections to Total Maintenance Material Cost

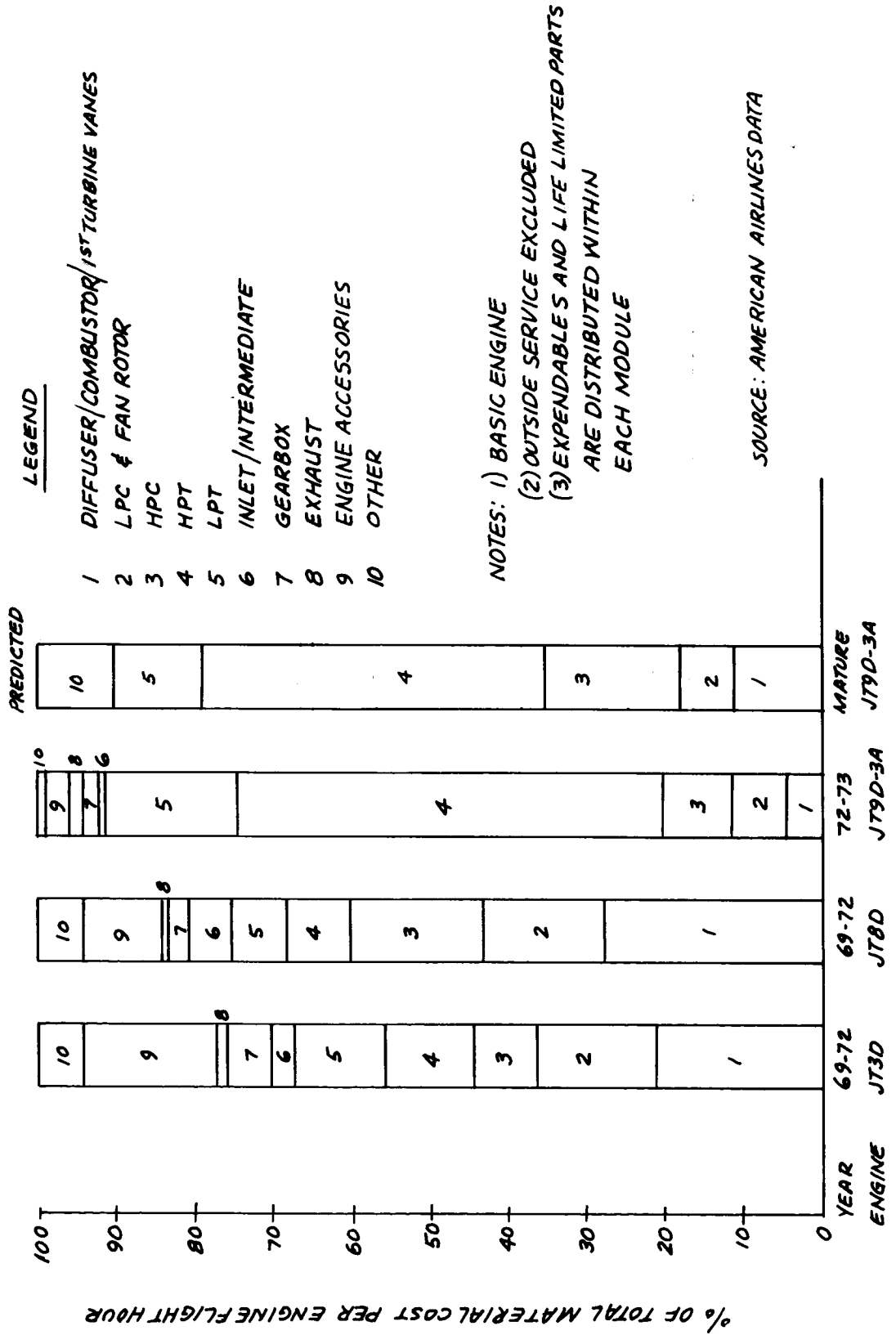


Figure III-36 Relative Contribution of Engine Module Sections to Total Maintenance Material Cost

REV. 4-4-74

MODULEPRIME HIGH COST PARTS INCLUDED IN MODULES

- | | |
|--------------------------|---|
| 1. FAN/LPC | Airfoils, Disks, Hubs, Rotating Seals, Tierods. |
| 2. HPC | Airfoils (except HPC exit guide vanes), disks, hubs, rotating seals, tierods. |
| 3. Diffuser | Bearings (HPC rear, HPT front, intershaft), HPC exit guide vanes, bearing housings. |
| 4. Combustor | Combustion chamber liners, turbine nozzle guide vanes, 1st turbine blade static tip seal, hot section piping and miscellaneous static combustion chamber parts. |
| 5. High Pressure Turbine | Airfoils (except NGV), disks, shaft, 2nd blade tip seal, 2nd stage inner seal. |
| 6. Low Pressure Turbine | Airfoils, disks, shaft, rotating seals and spacers, blade tip seals, rear bearing. |

Figure III-37 Description of Prime High Cost Parts Included in Modules

REV. 4-8-74

SOURCE: AMERICAN AIRLINES DATA

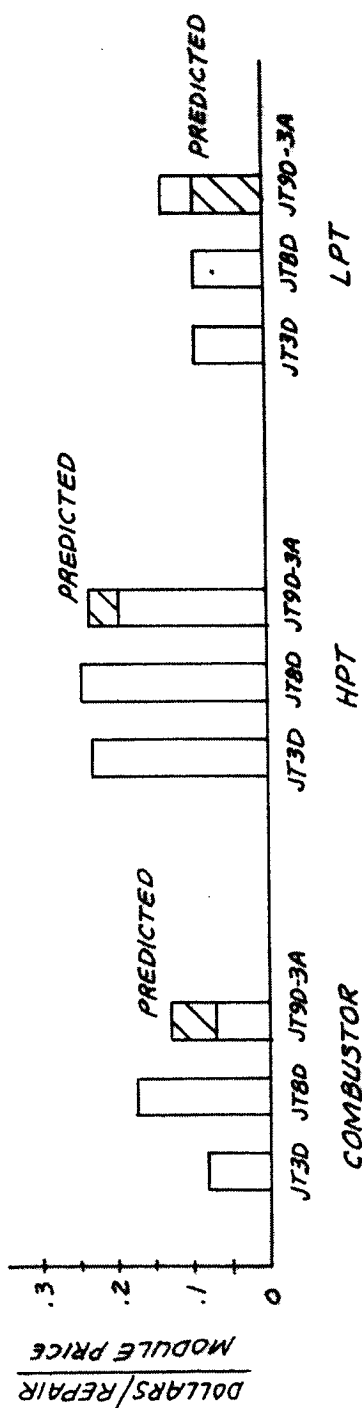
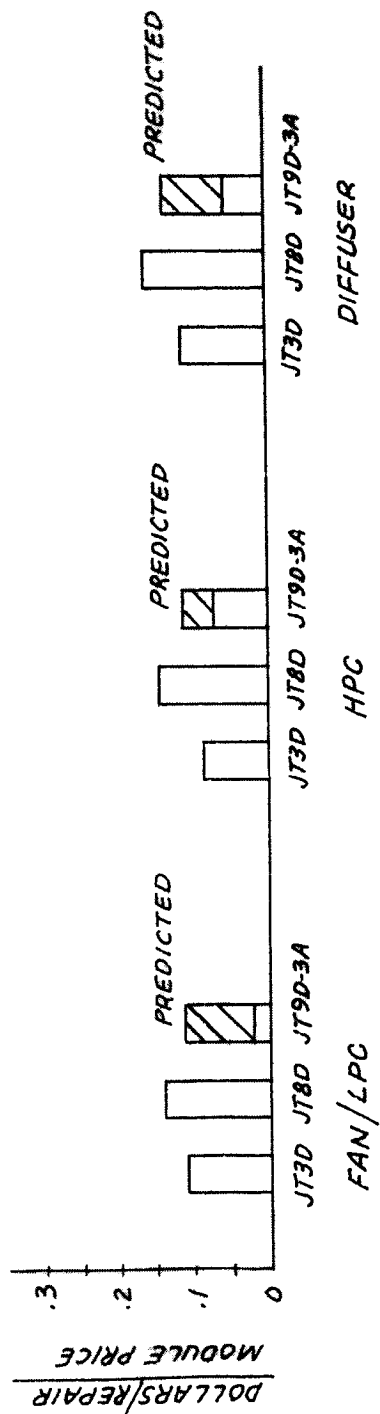


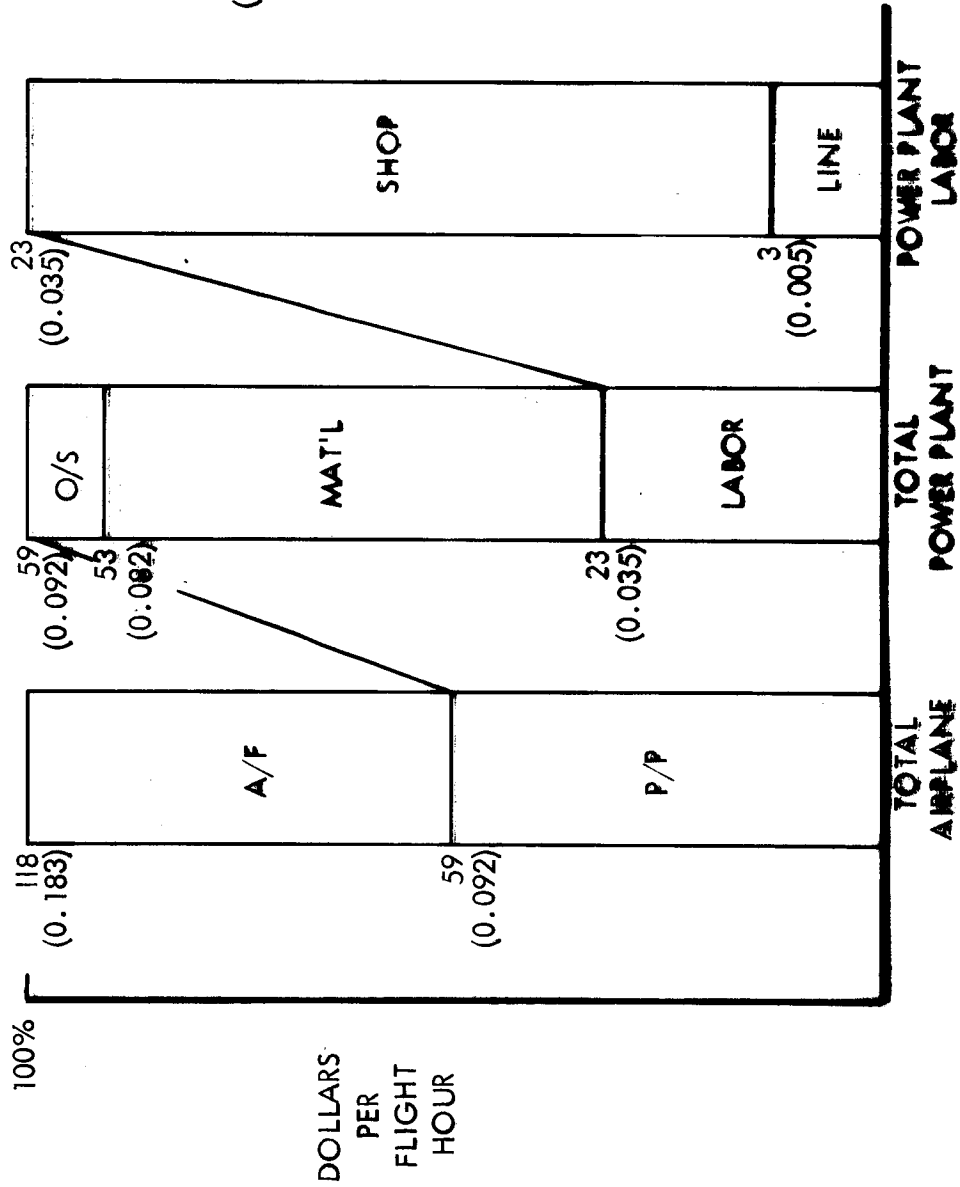
Figure III-37 A Module Material Cost per Repair Normalized by Module Price are Essentially Constant Between Engines

REV. 4-4-74

707-123B DIRECT MAINTENANCE COST

YEAR 1972

● AVERAGE FLIGHT LENGTH - 2.2 HOURS



() = CENTS / SEAT MILE

727 DIRECT MAINTENANCE COST

YEAR 1972 (FLEET AVERAGE AND AA)

● AVERAGE FLIGHT LENGTH - 1.2 HOURS

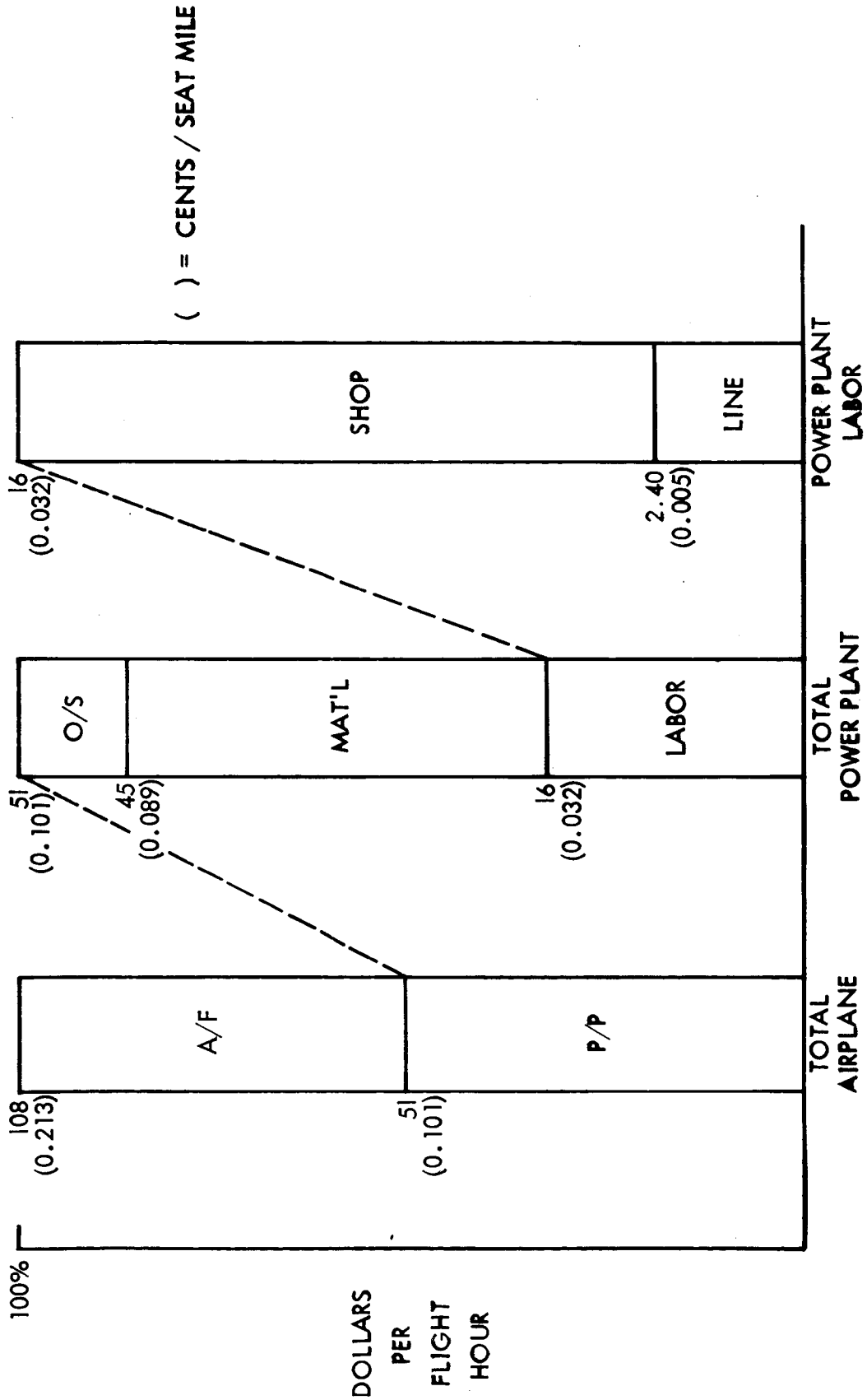


Figure III-39

747 DIRECT MAINTENANCE COST

YEAR 1972

● AVERAGE FLIGHT LENGTH - 3.5 HOURS

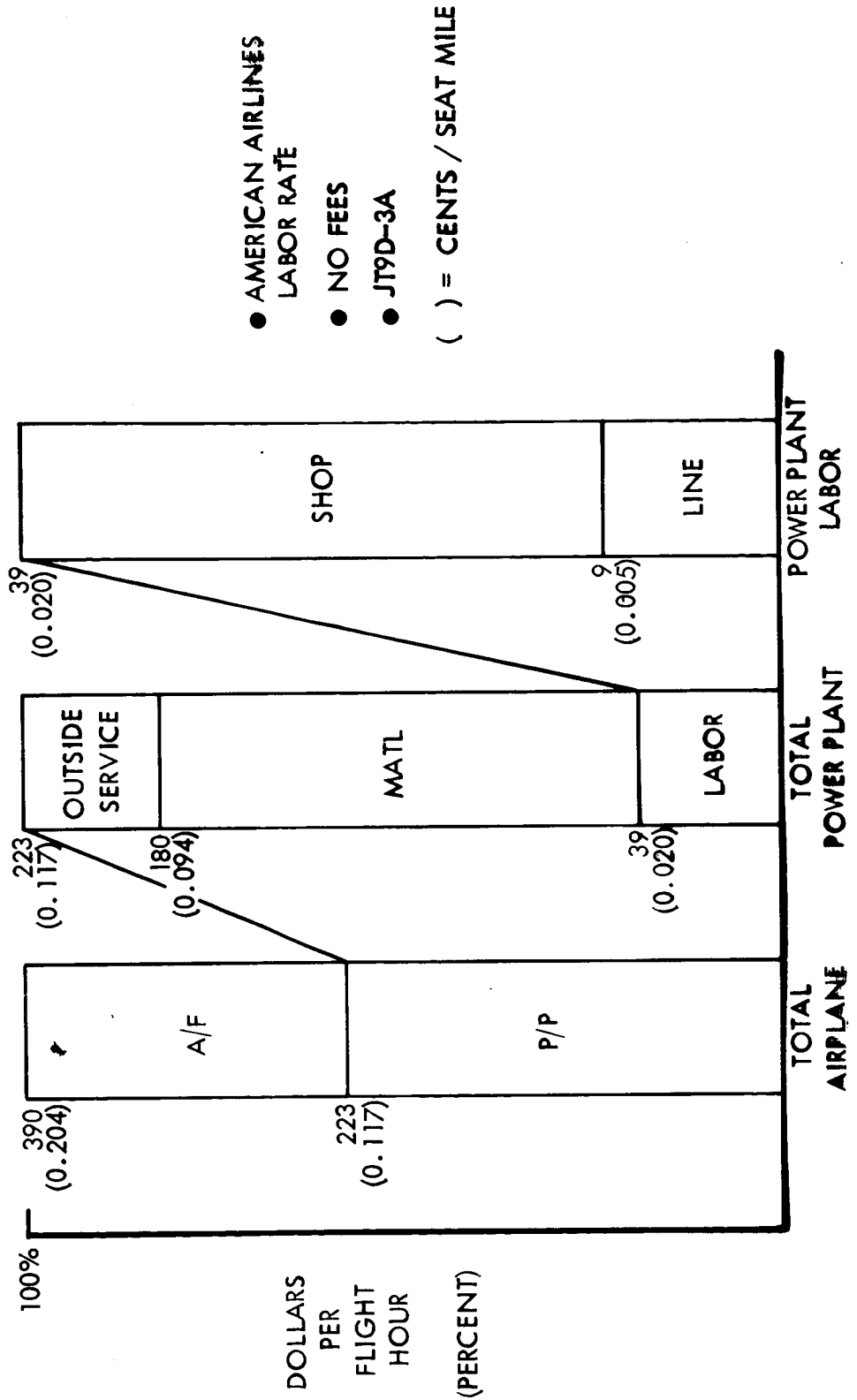


Figure III-40

707-123B DIRECT MAINTENANCE COST

DIRECT LABOR, MATERIAL & OUTSIDE SERVICE
YEAR 1972

● AVERAGE FLIGHT LENGTH - 2.2 HOURS

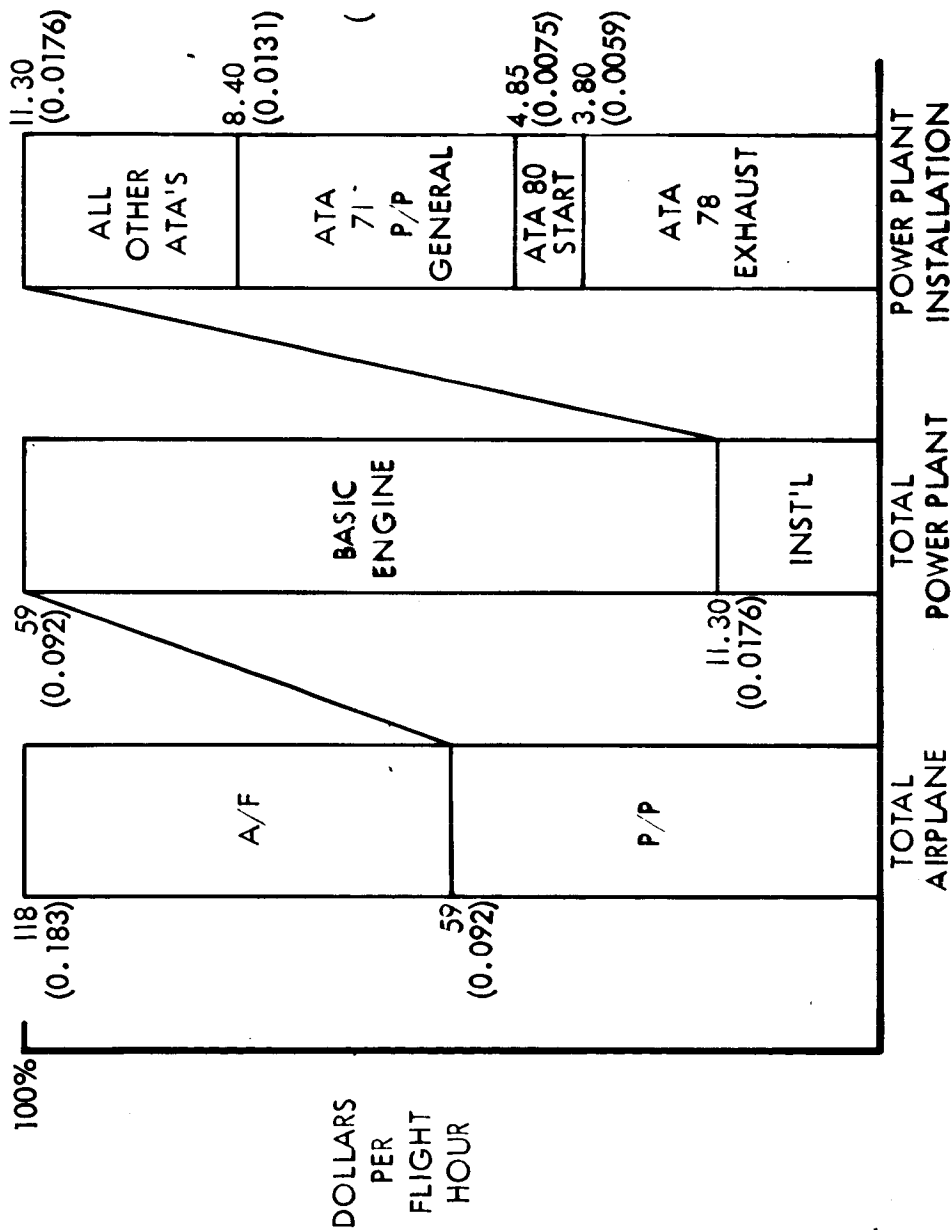


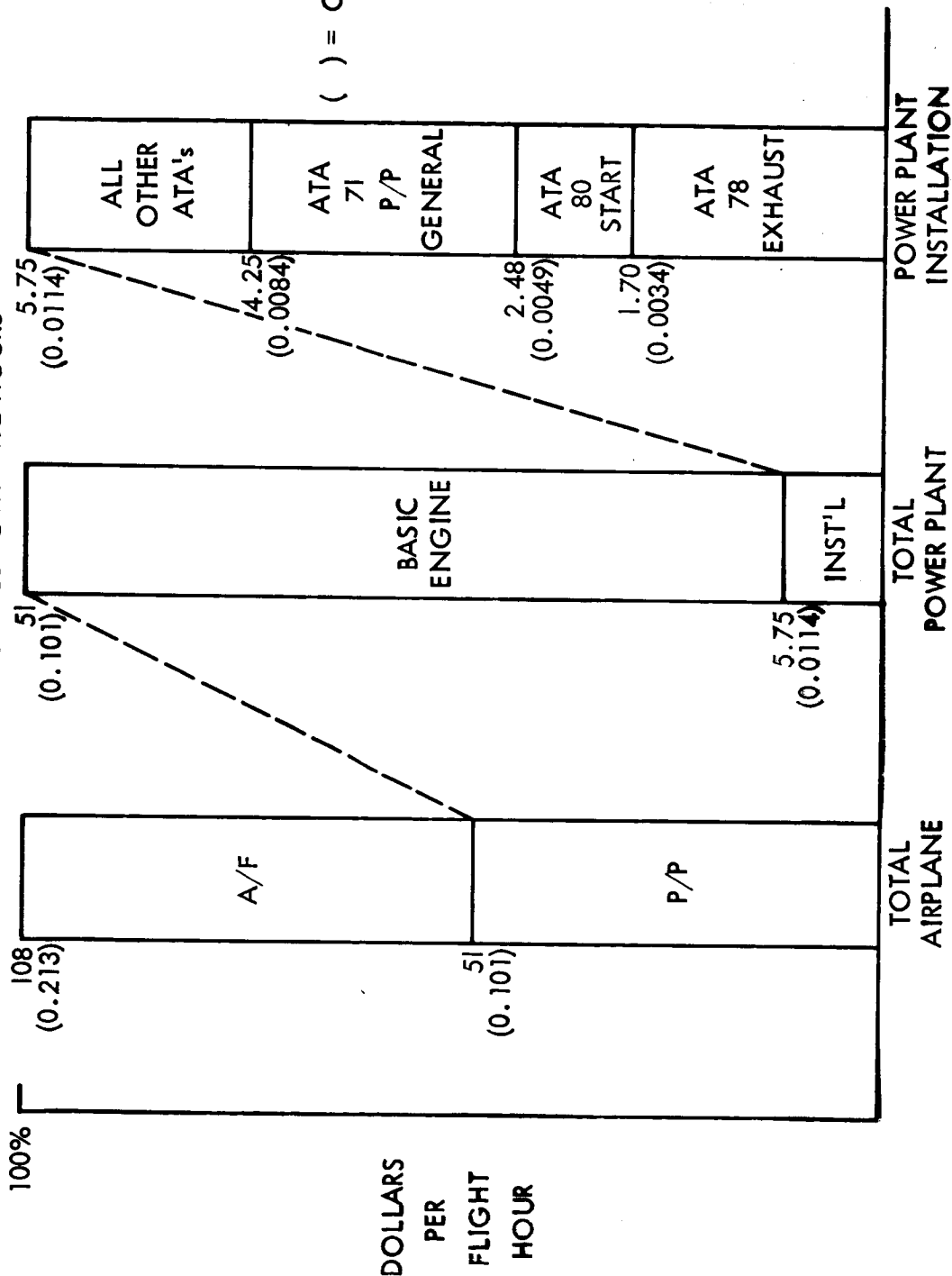
Figure III-41

727 DIRECT MAINTENANCE COST

DIRECT LABOR, MATERIAL & OUTSIDE SERVICE

YEAR 1972

● AVERAGE FLIGHT LENGTH - 1.2 HOURS



() = CENTS / SEAT MILE

Figure III-42

747 DIRECT MAINTENANCE COST

DIRECT LABOR, MATERIAL & OUTSIDE SERVICE
YEAR 1972

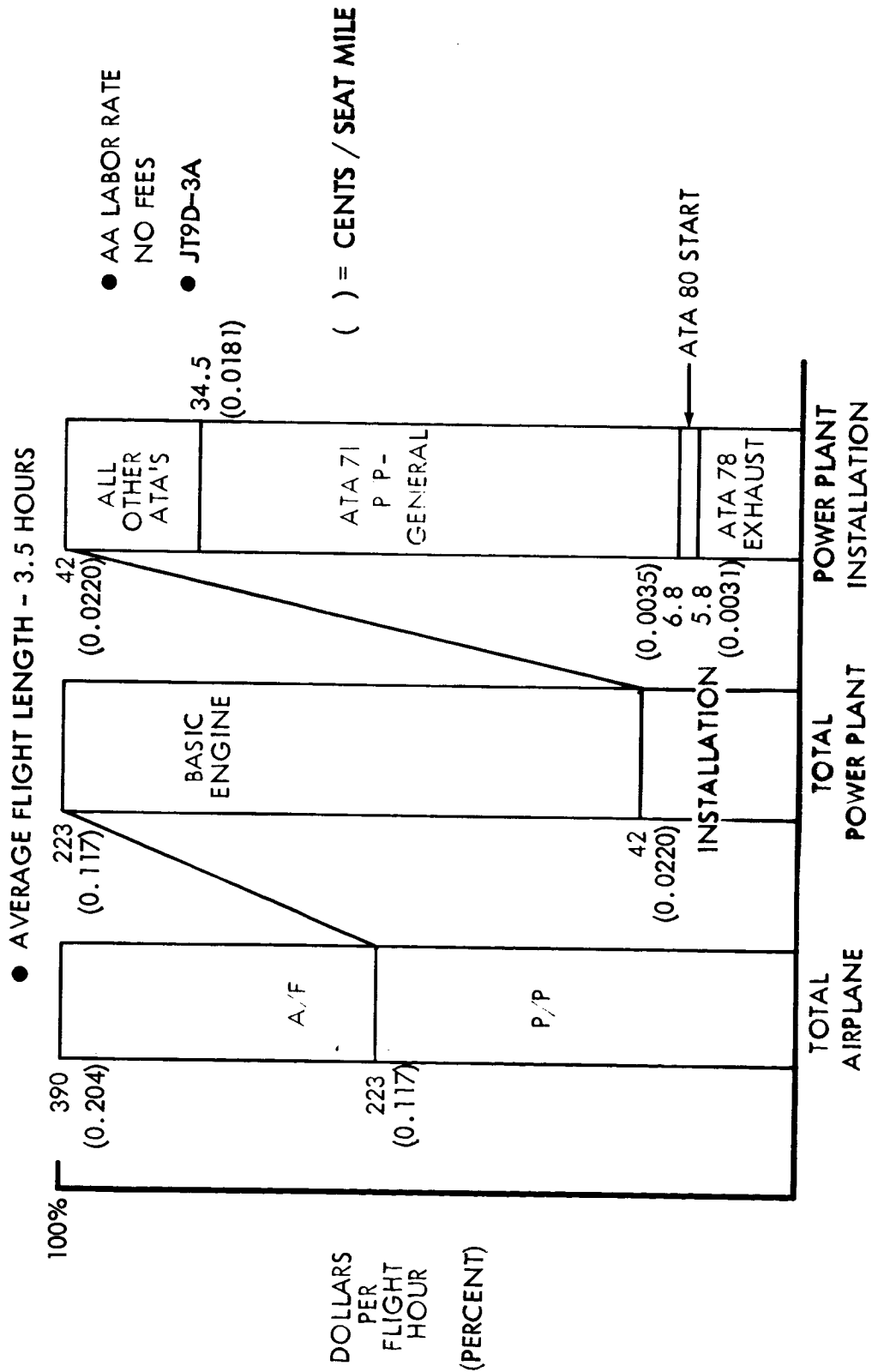


Figure III-43

ENGINE - LABOR ALL MODELS

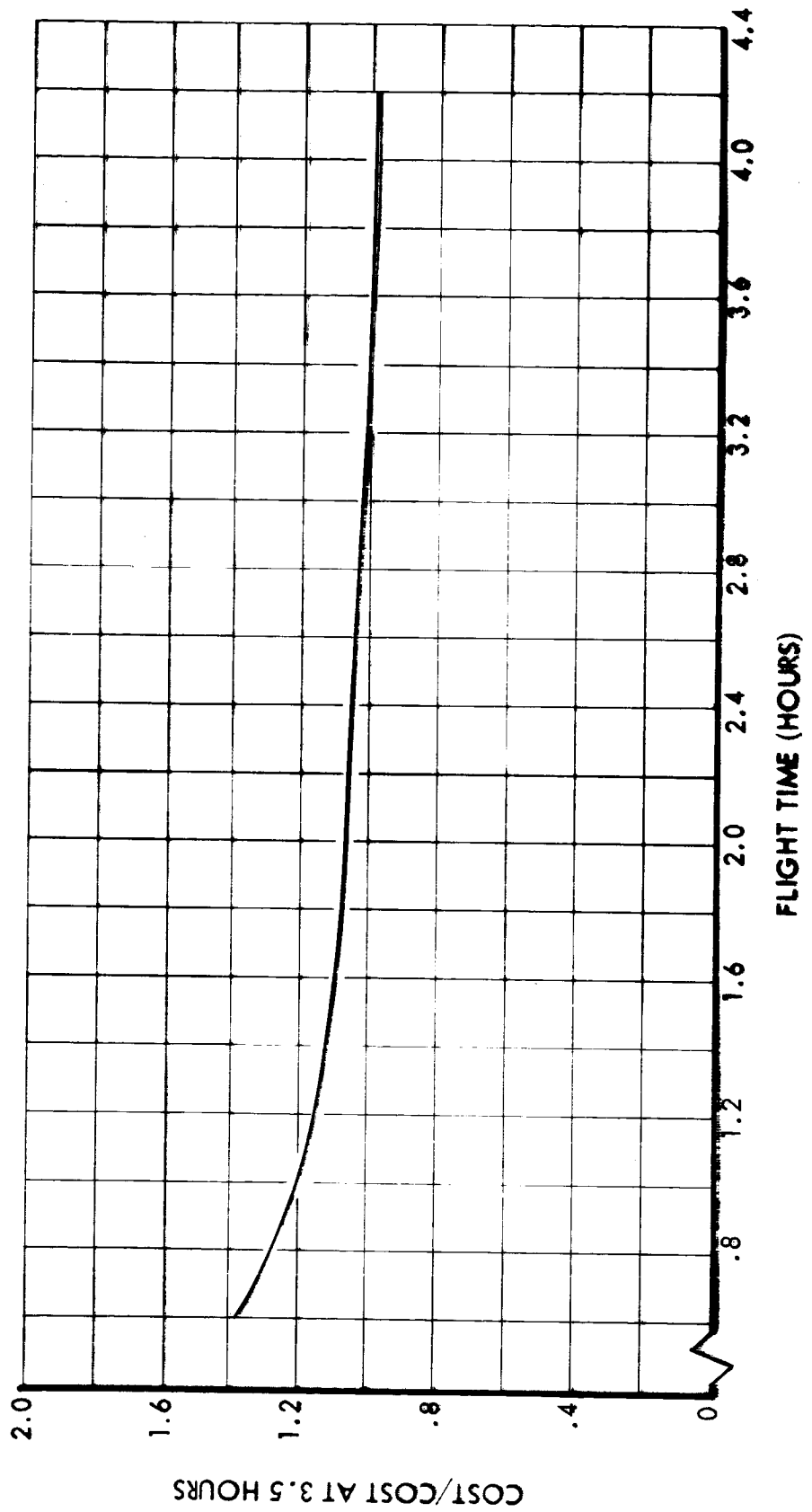


Figure III-44

5-574

ENGINE - MATERIAL

ALL MODELS

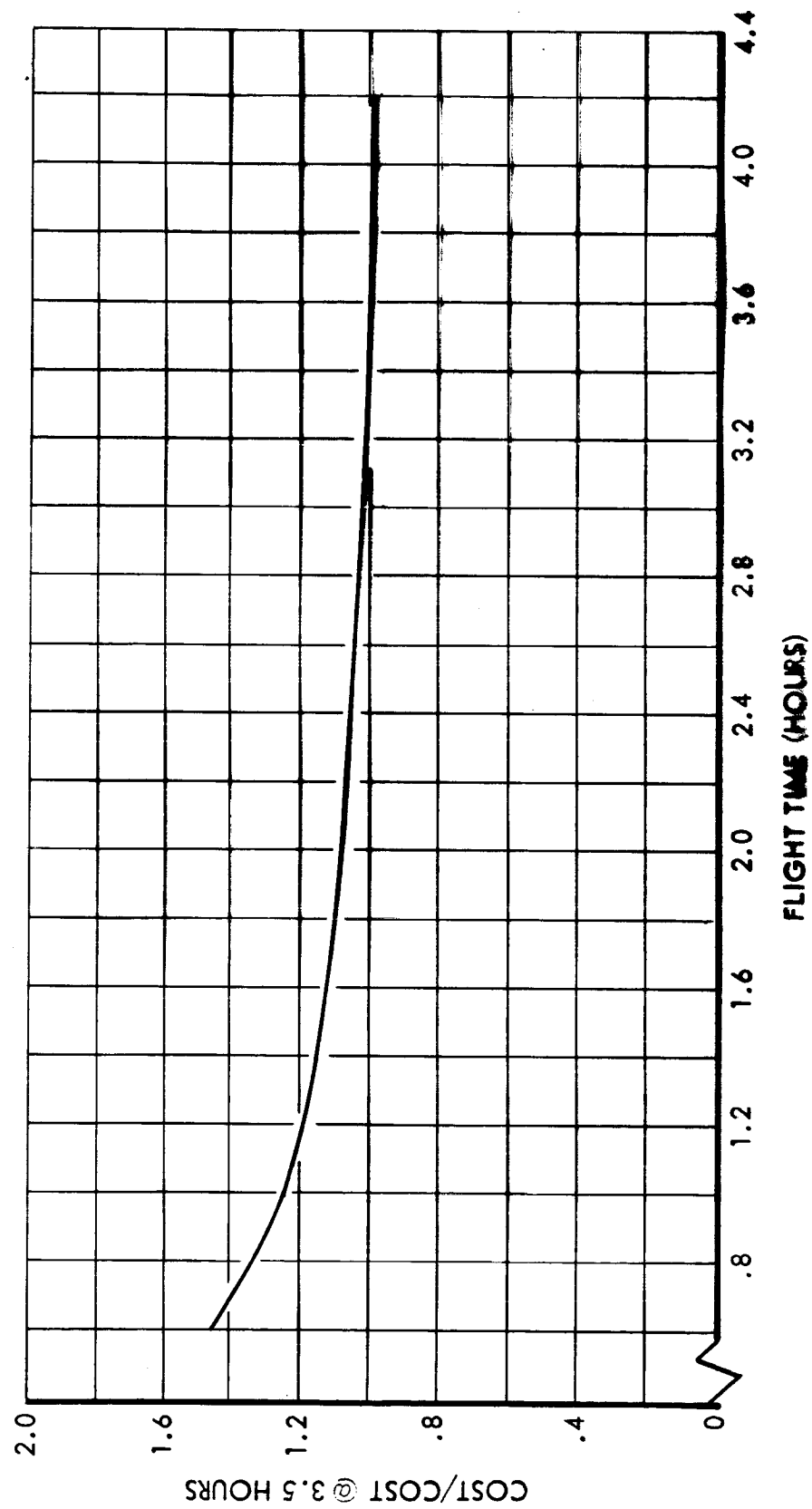


FIGURE III-45

POWER PLANT SYSTEMS

LINE MAINTENANCE - DIRECT LABOR ONLY

1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

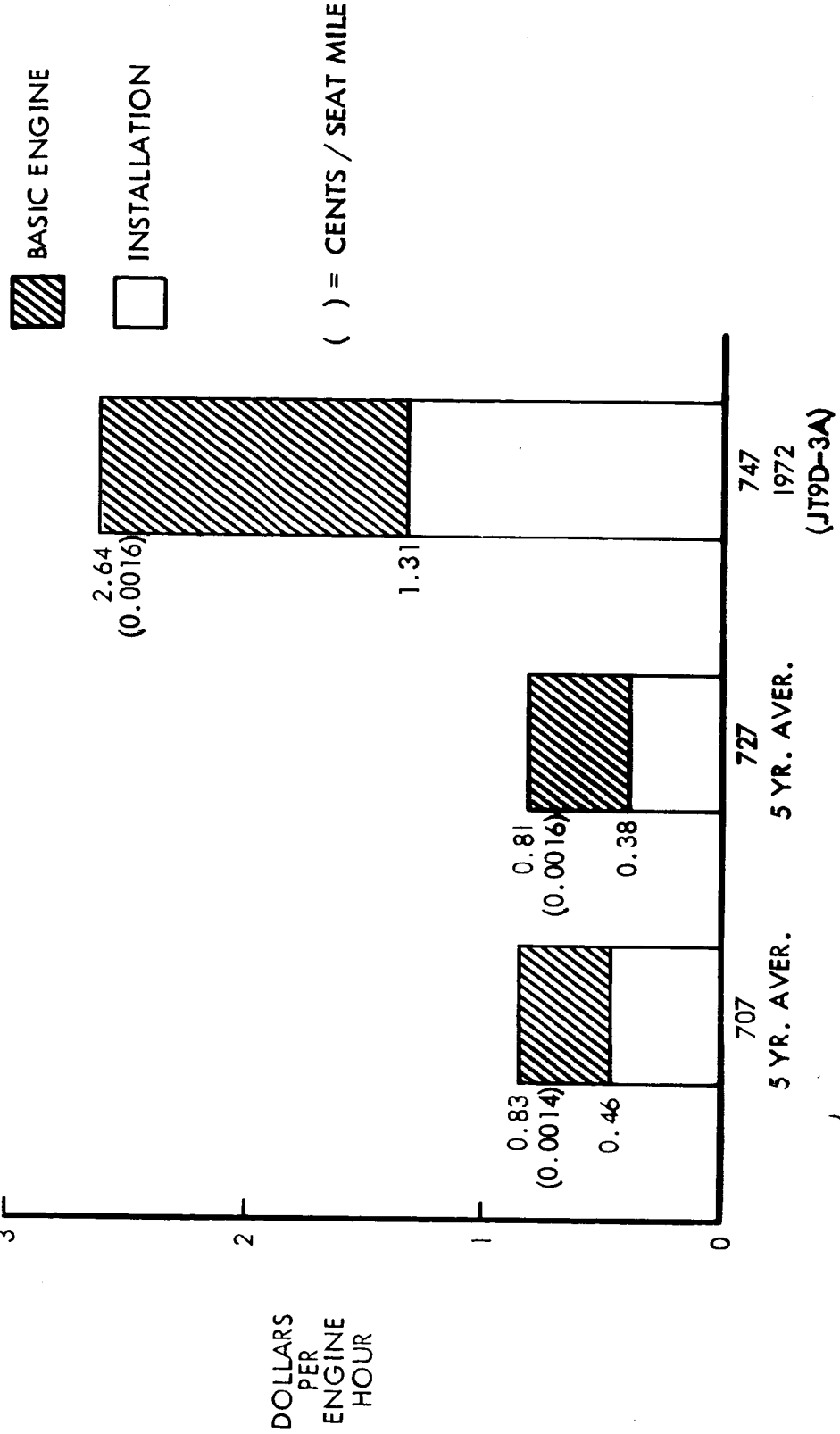


Figure III-46

POWER PLANT SYSTEMS

SHOP MAINTENANCE - DIRECT LABOR ONLY
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

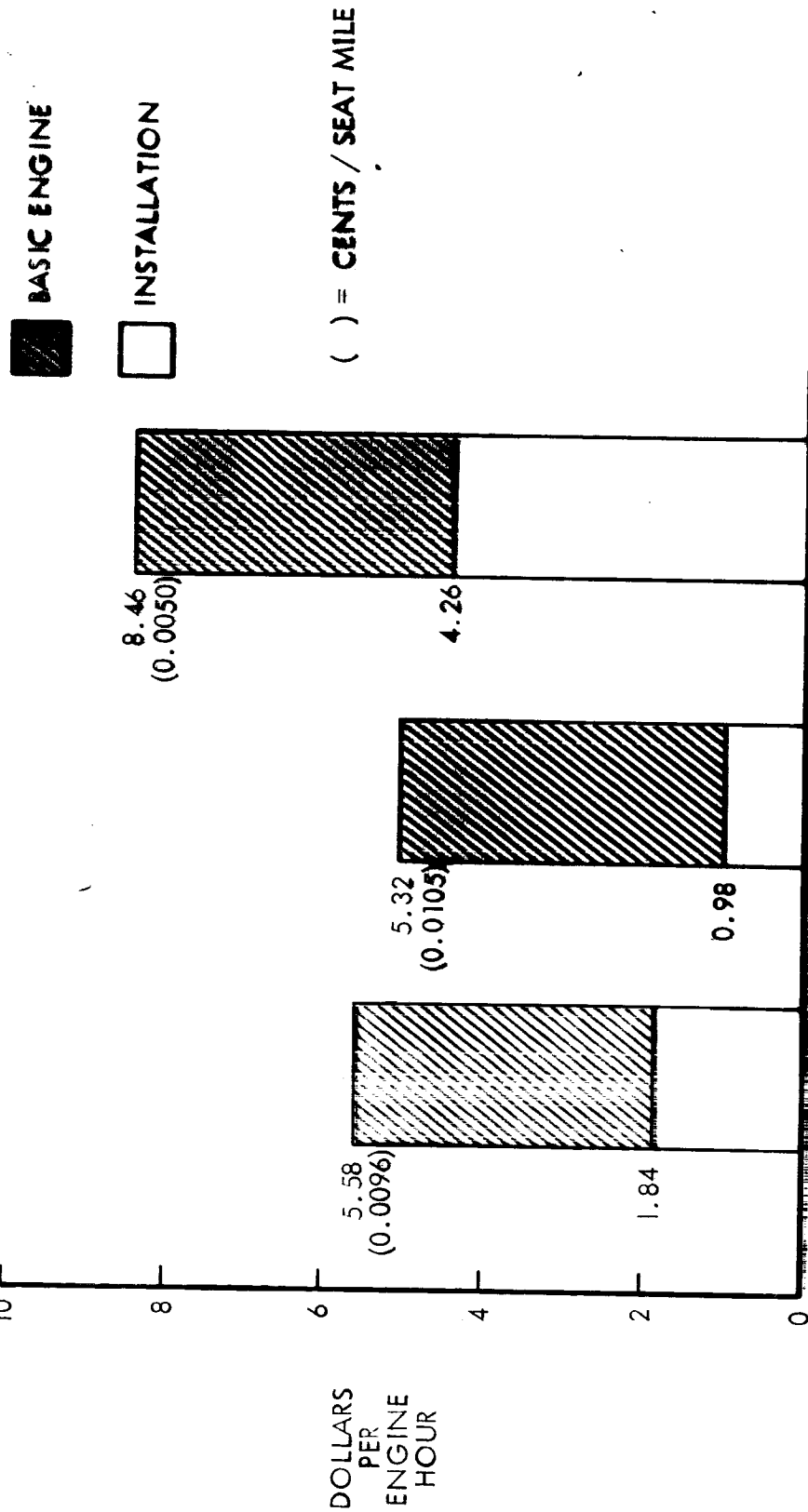


Figure III-47

POWER PLANT SYSTEMS

SHOP MATERIAL
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

■ BASIC ENGINE
□ INSTALLATION
() = CENTS / SEAT MILE

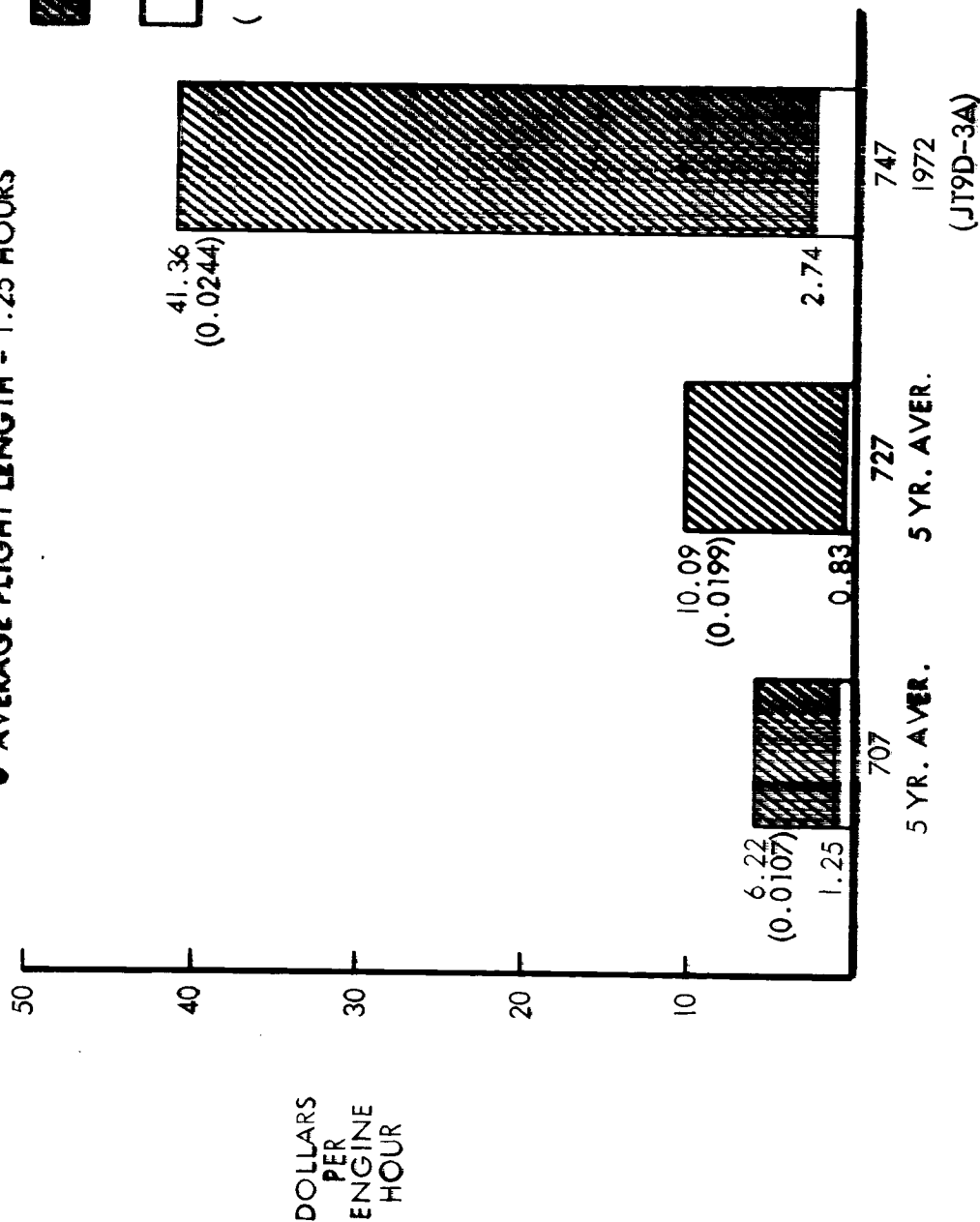


Figure III-48

4-3-74

POWER PLANT SYSTEMS

OUTSIDE SERVICES

1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

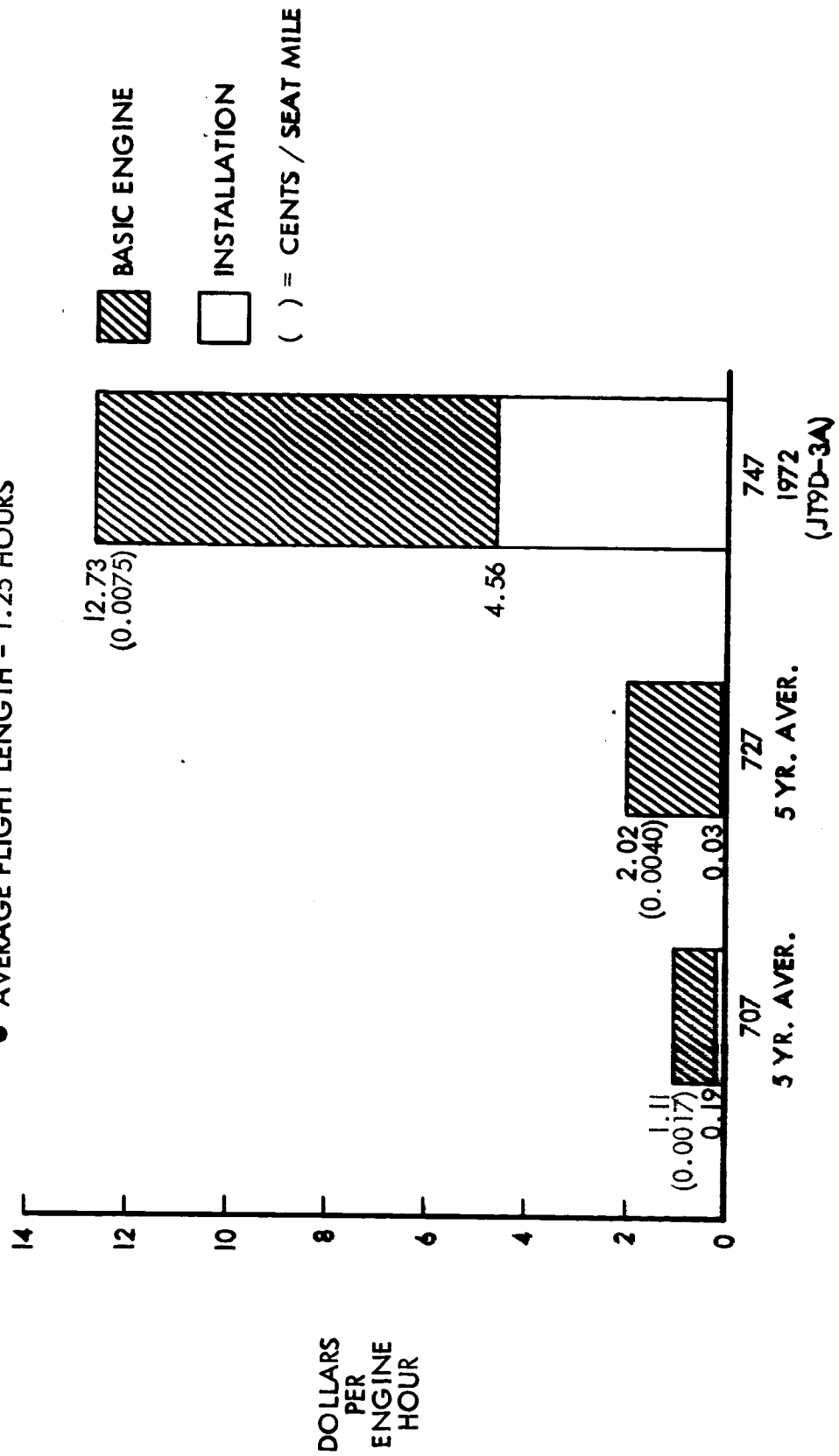


Figure III-49

POWER PLANT SYSTEMS

ATA 71 POWER PLANT - GENERAL (LABOR FULLY ALLOCATED)
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

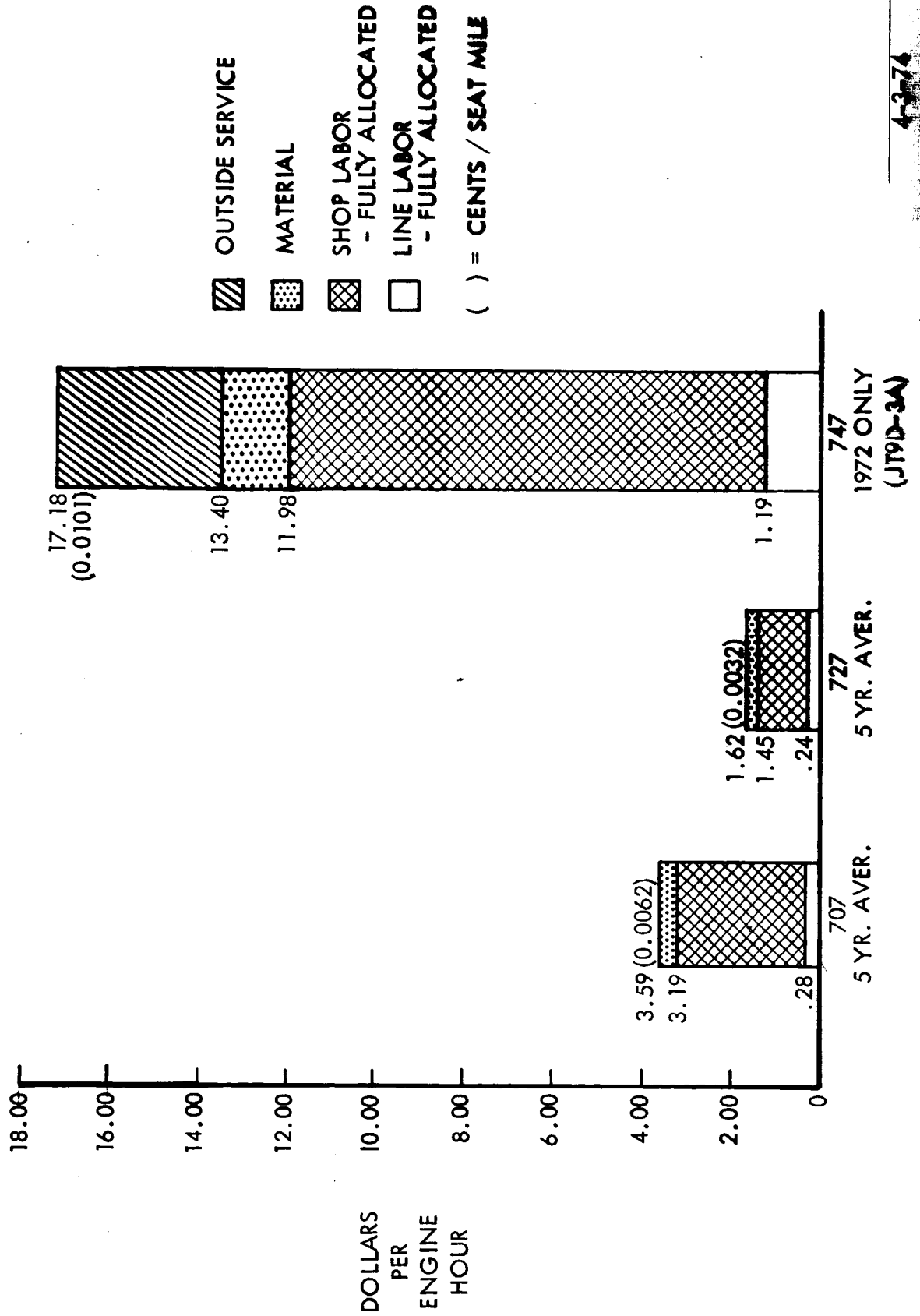


Figure III-50

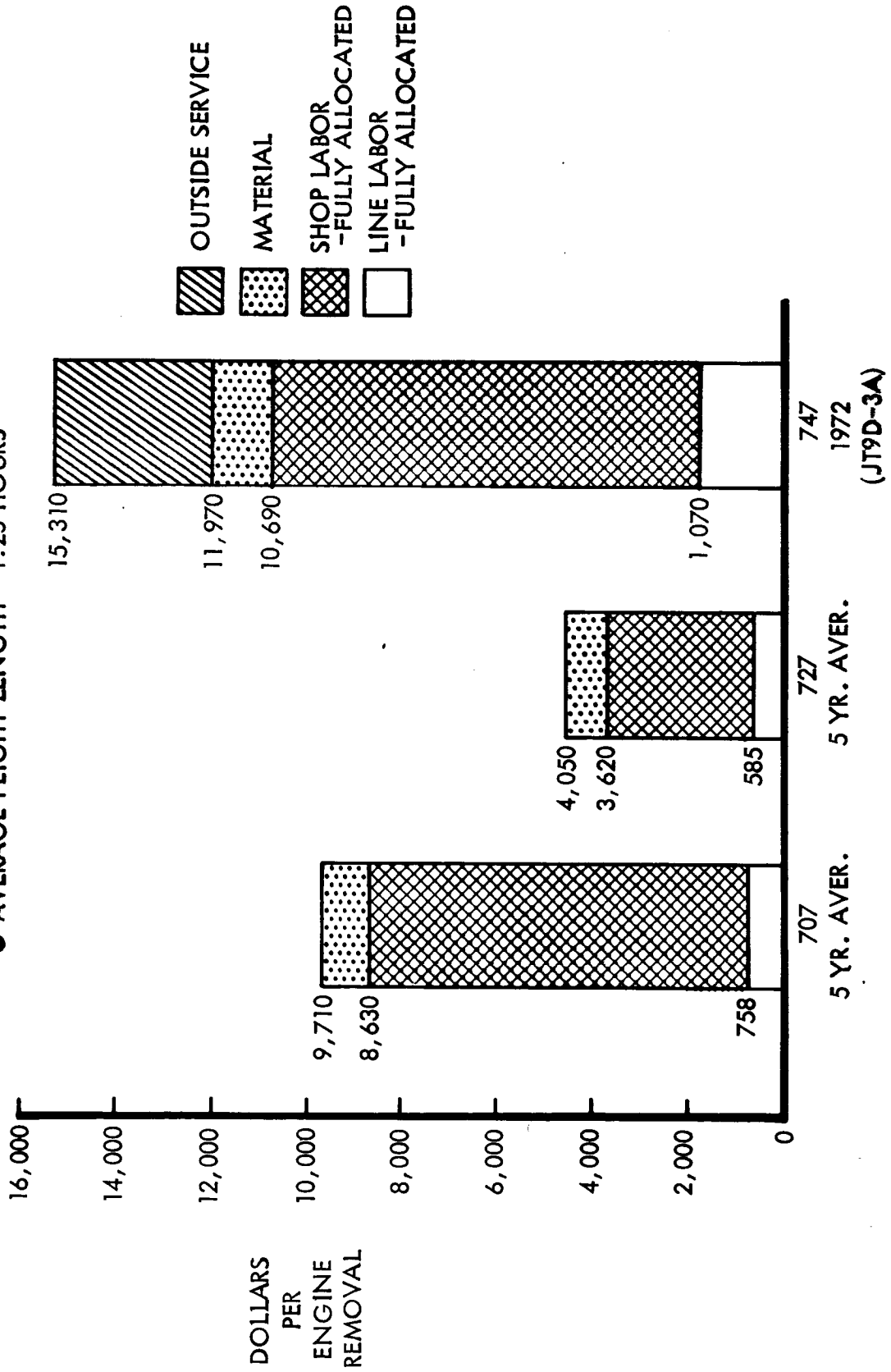
4-3-76

POWER PLANT SYSTEMS

ATA 71 POWER PLANT - GENERAL (LABOR FULLY ALLOCATED)

1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS



POWER PLANT SYSTEMS

ATA 71 POWER PLANT - GENERAL 1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

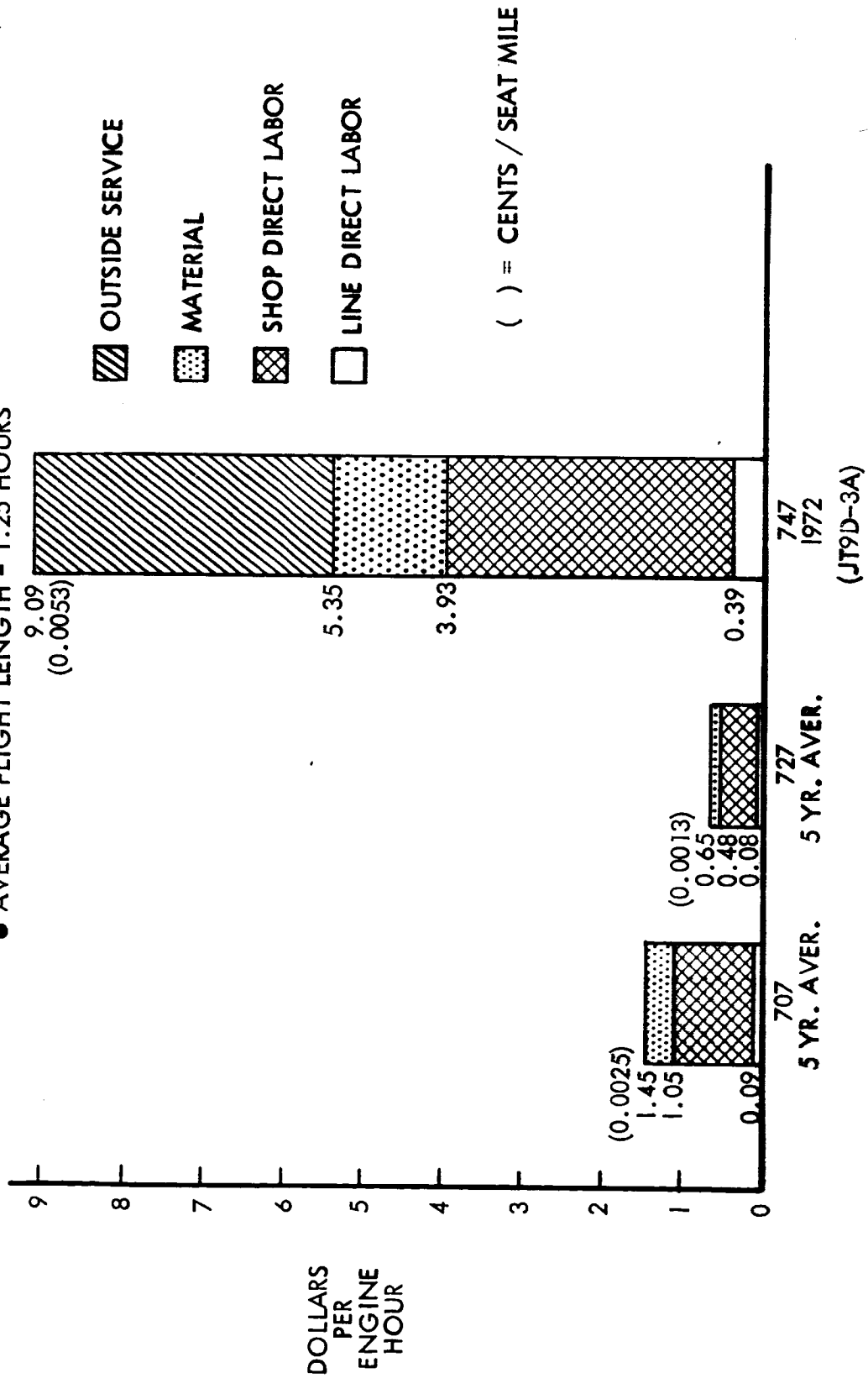


Figure III-51

POWER PLANT SYSTEMS

ATA 71 POWER PLANT - GENERAL

1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

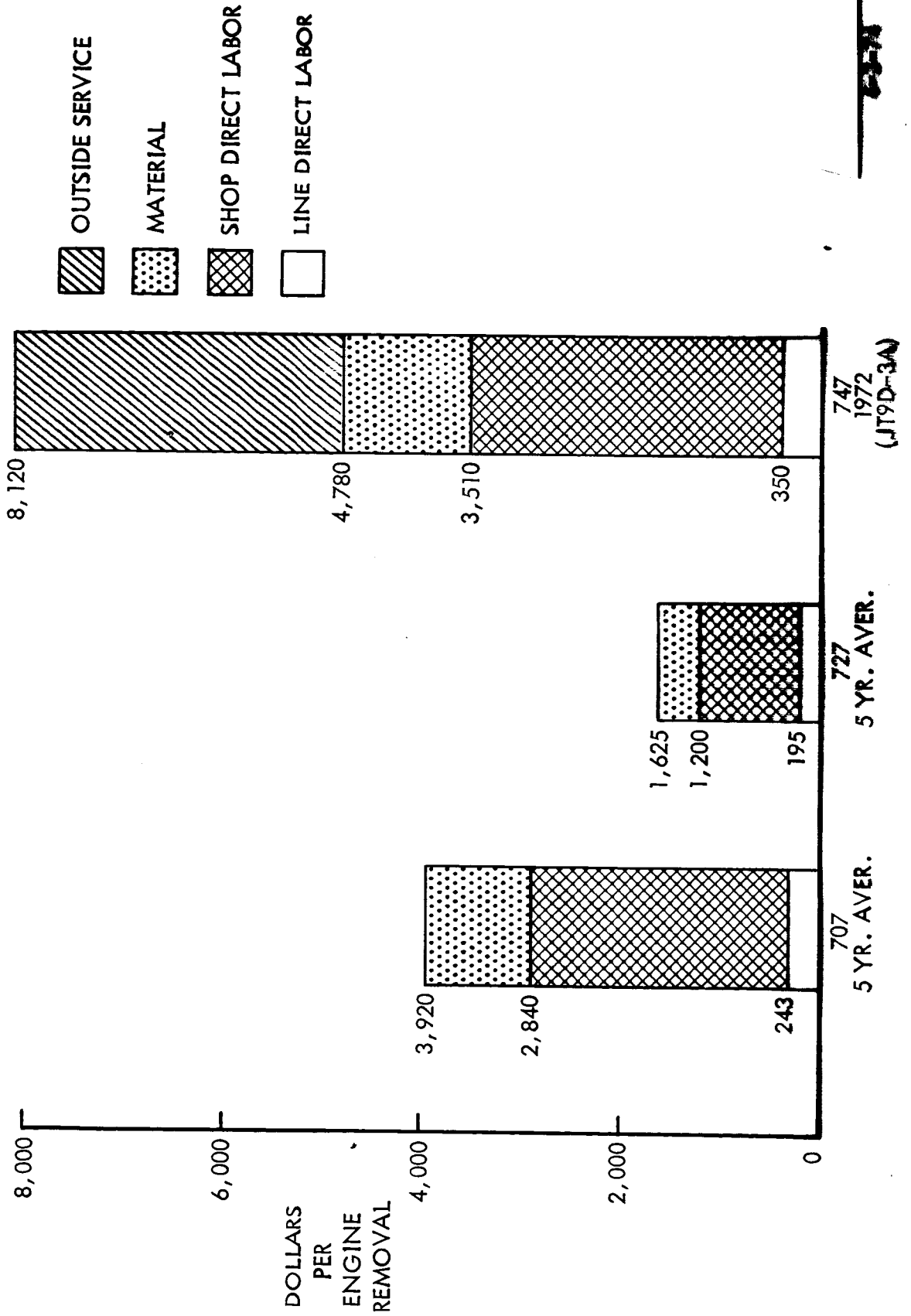


Figure III-51A

POWER PLANT SYSTEMS

ATA 78 EXHAUST (LABOR FULLY ALLOCATED)
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

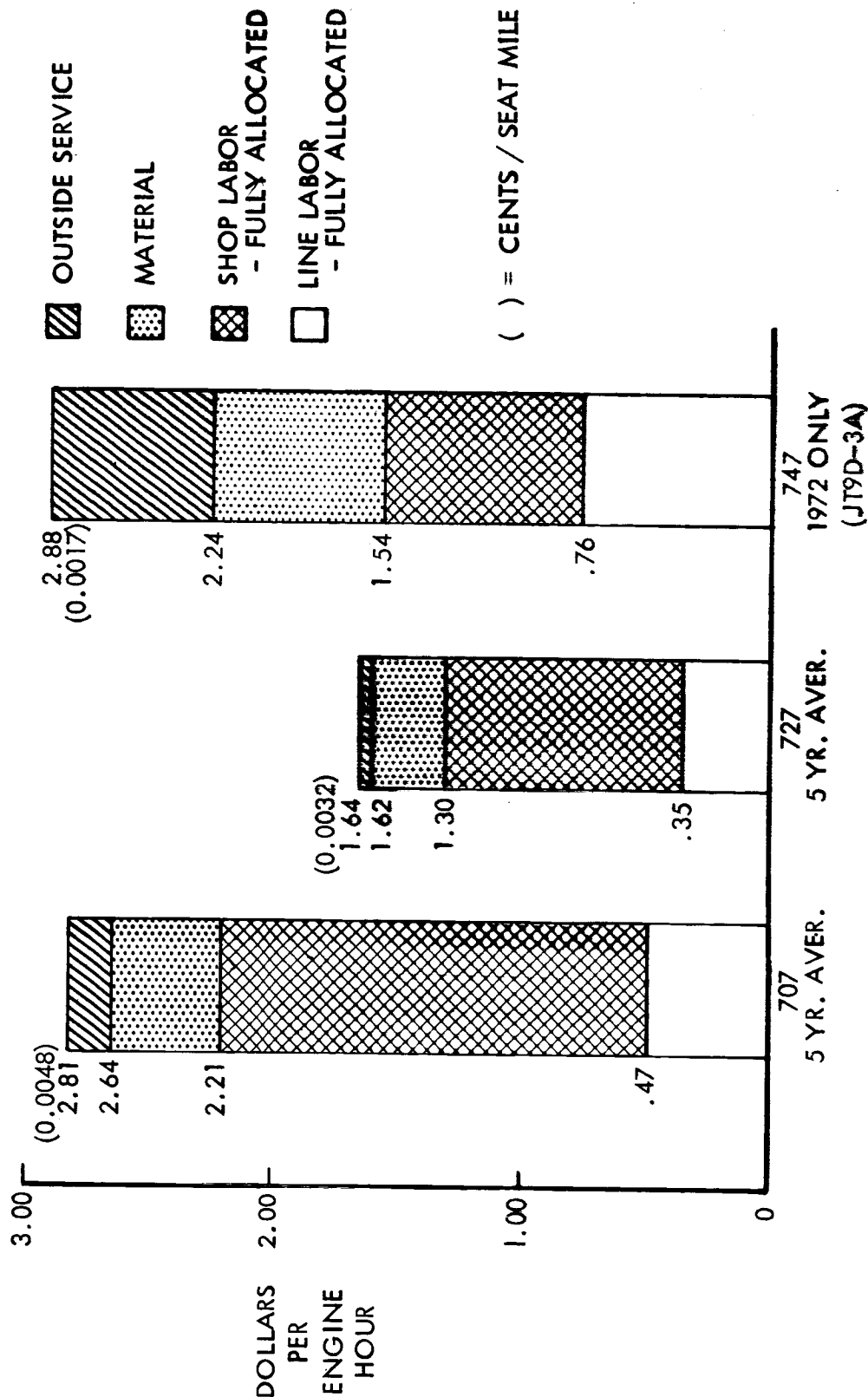


Figure III-52

POWER PLANT SYSTEMS

ATA 78 EXHAUST
1972 DOLLARS

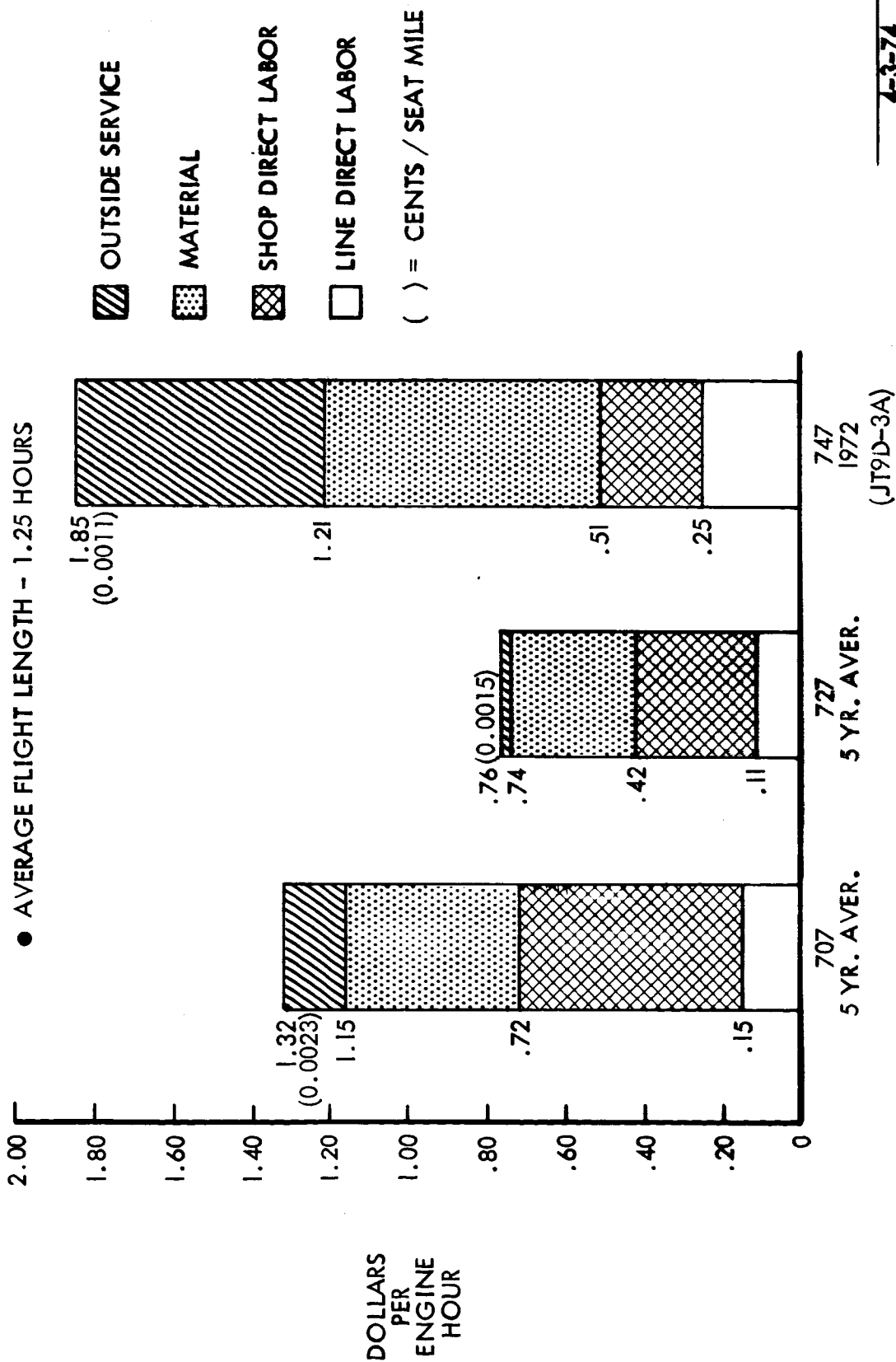


Figure III-53

POWER PLANT SYSTEMS

ATA 80 STARTING (LABOR FULLY ALLOCATED)
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

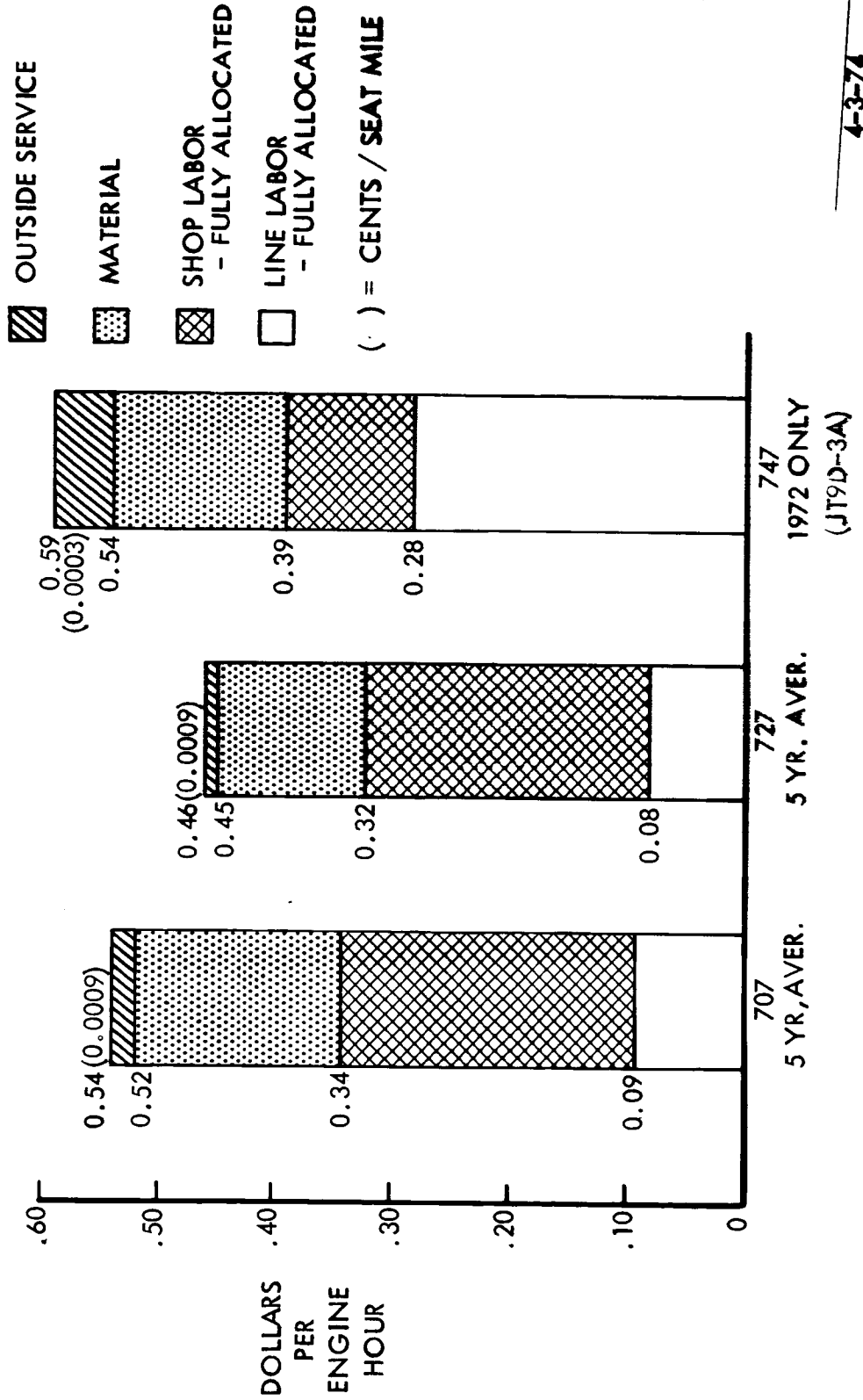


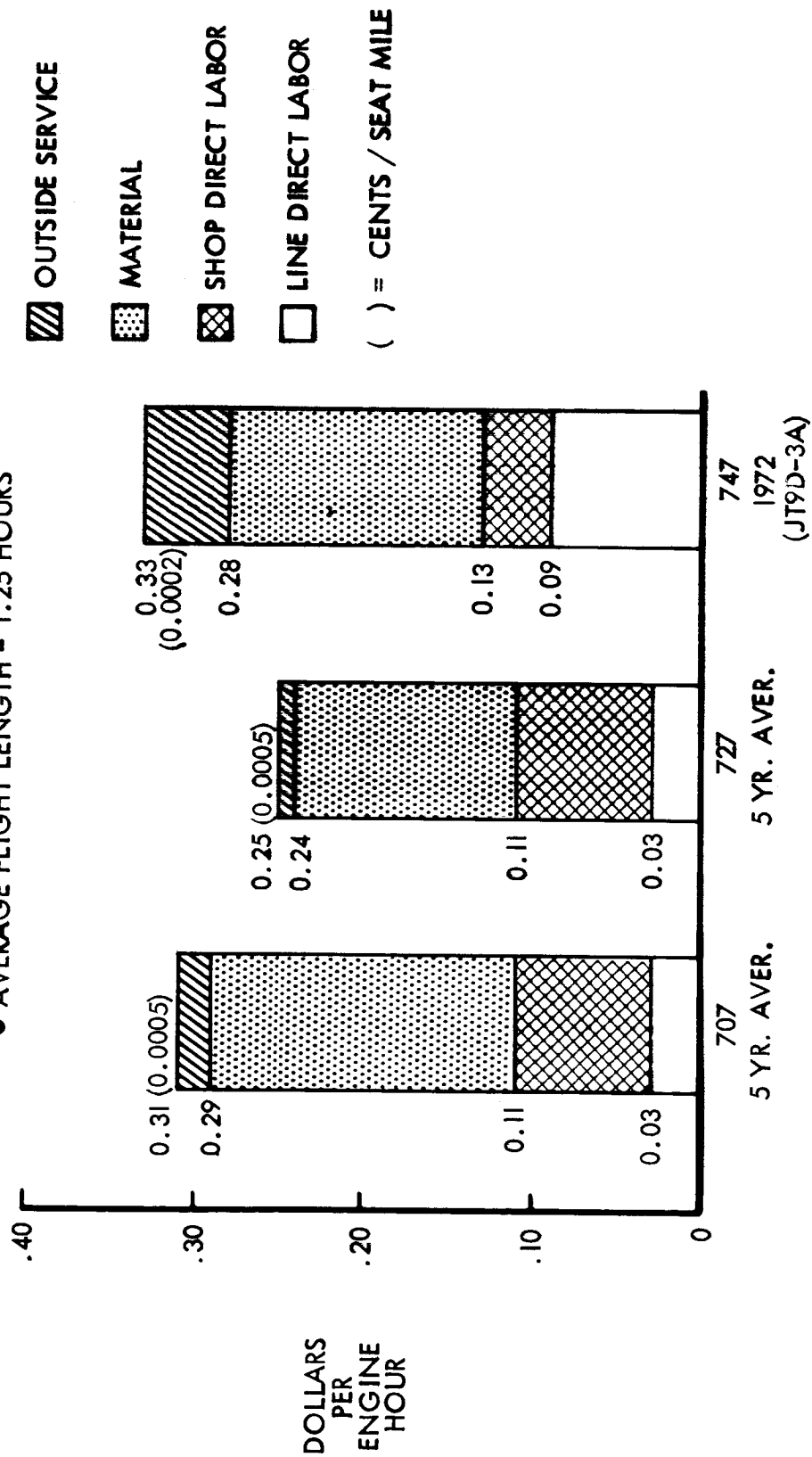
Figure III-54

4-3-74

POWER PLANT SYSTEMS

ATA 80 STARTING
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS



POWER PLANT SYSTEMS

ALL OTHER ATA'S (LABOR FULLY ALLOCATED)
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

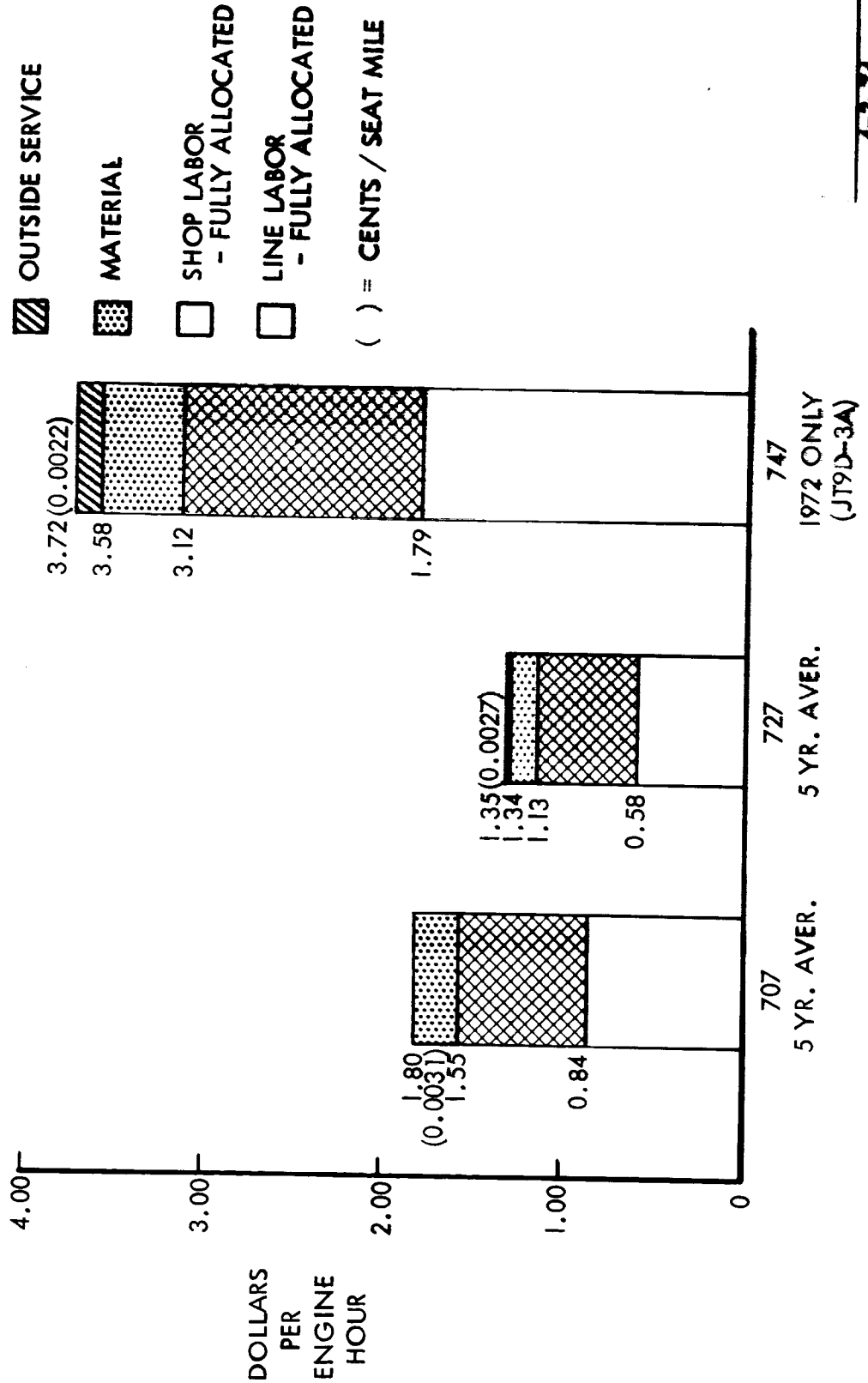


Figure III-56

POWER PLANT SYSTEMS

ALL OTHER ATA'S
1972 DOLLARS

● AVERAGE FLIGHT LENGTH - 1.25 HOURS

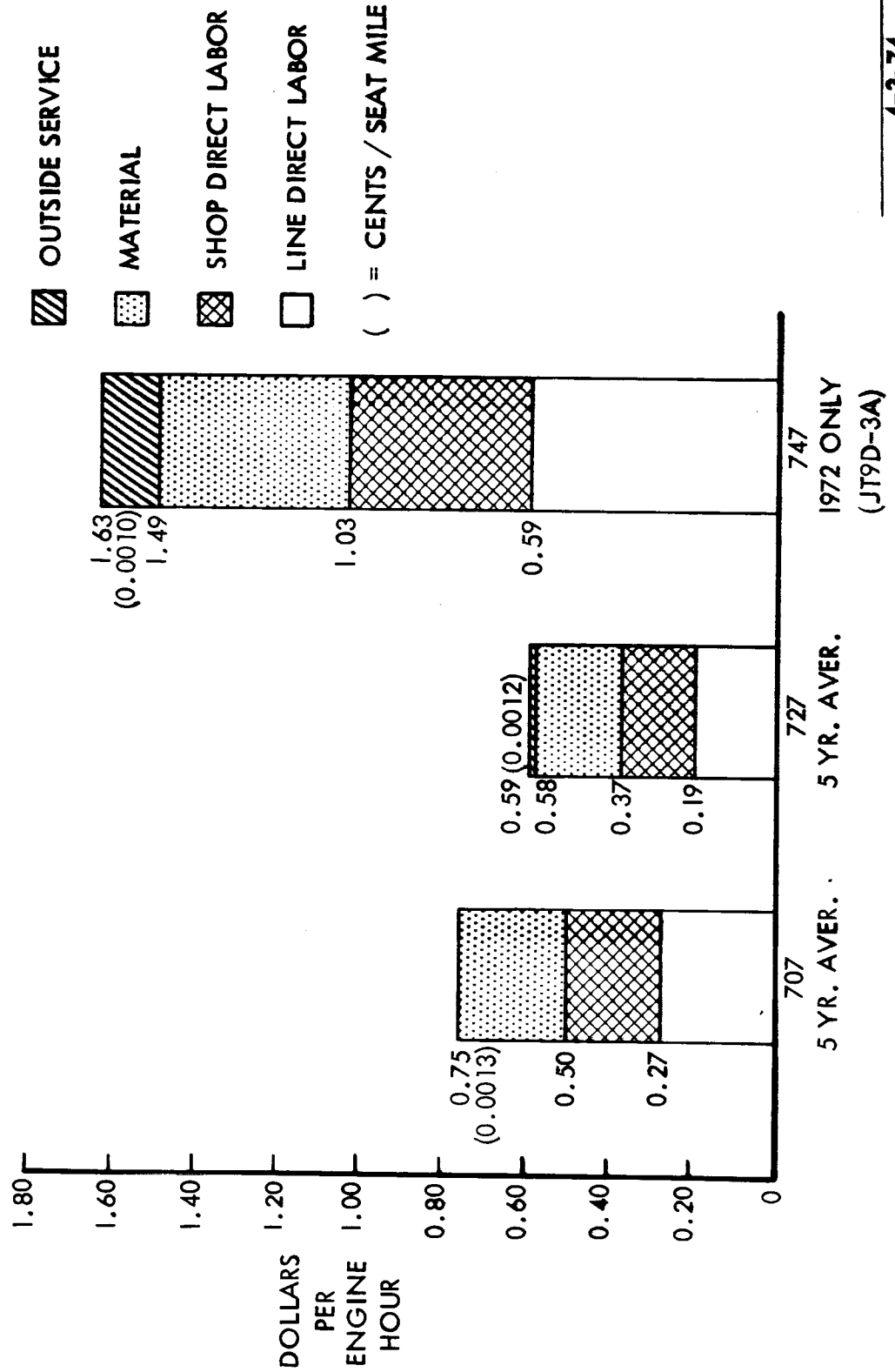


Figure III-57

MECHANICAL SCHEDULE RELIABILITY HISTORY

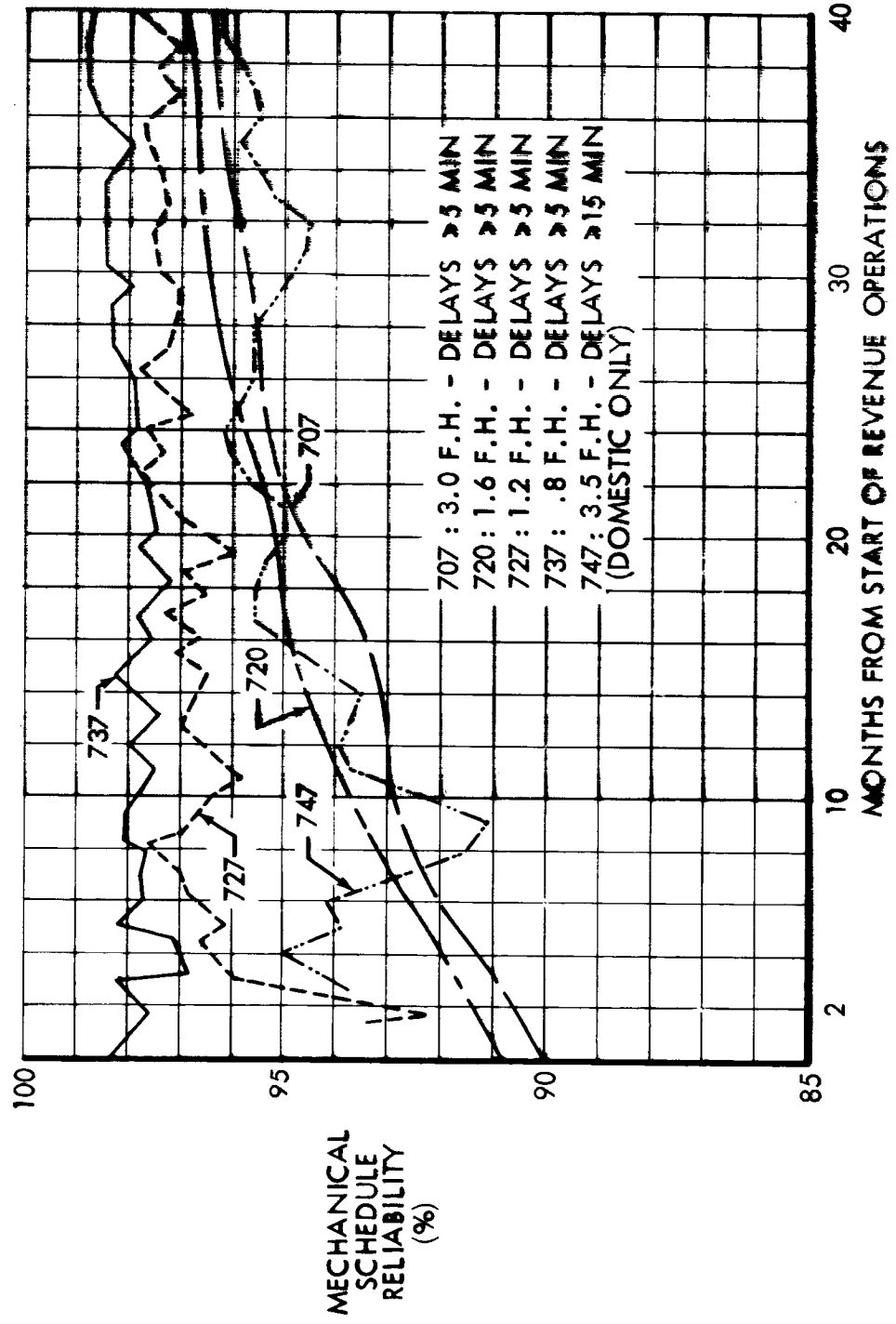


FIGURE III-58

POWER PLANT SYSTEMS

YEAR 1972

● ONE U.S. AIRLINE

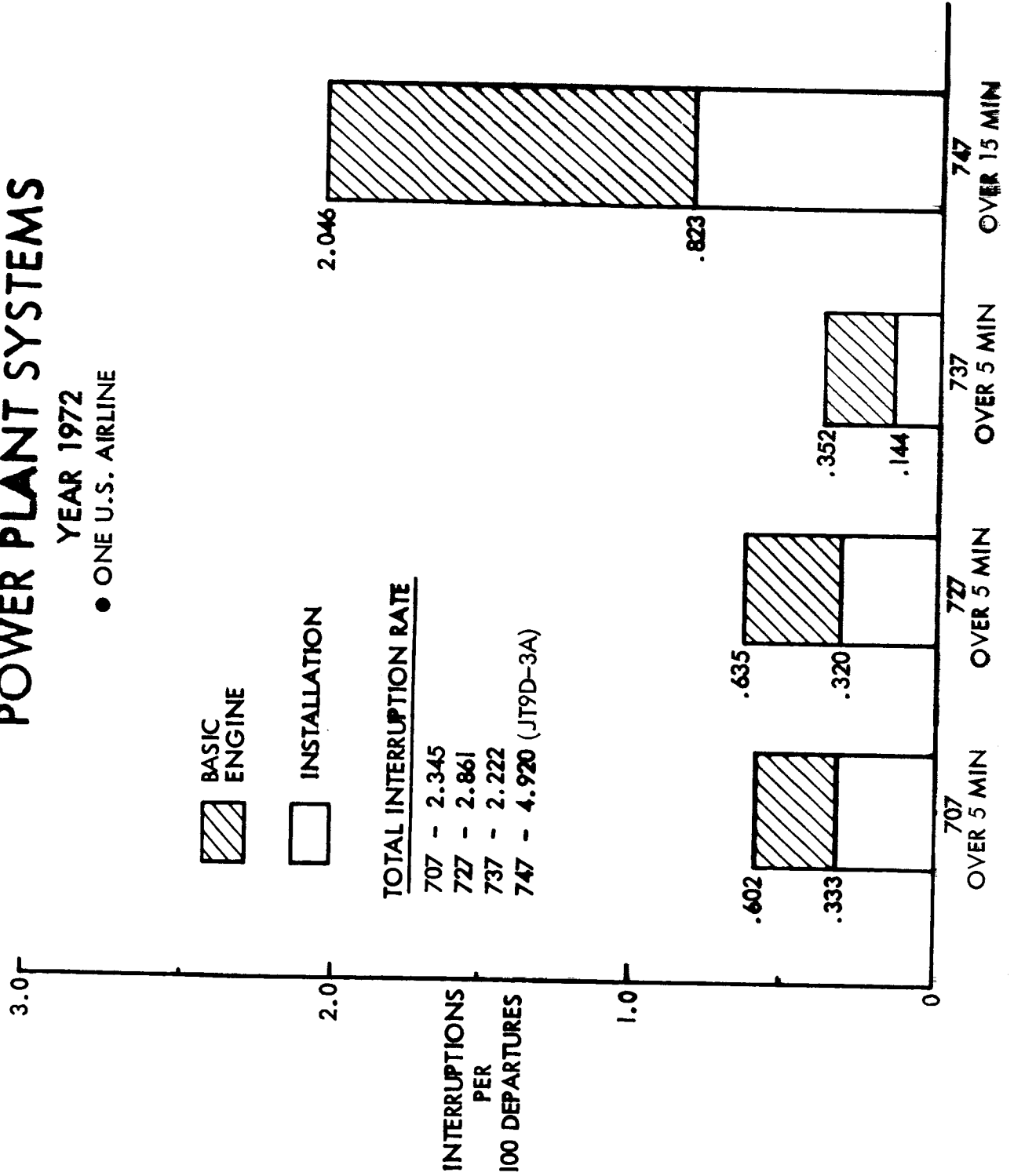


FIGURE III-59

707 INTERRUPTION RATE

YEAR 1972

● ONE U.S. AIRLINE

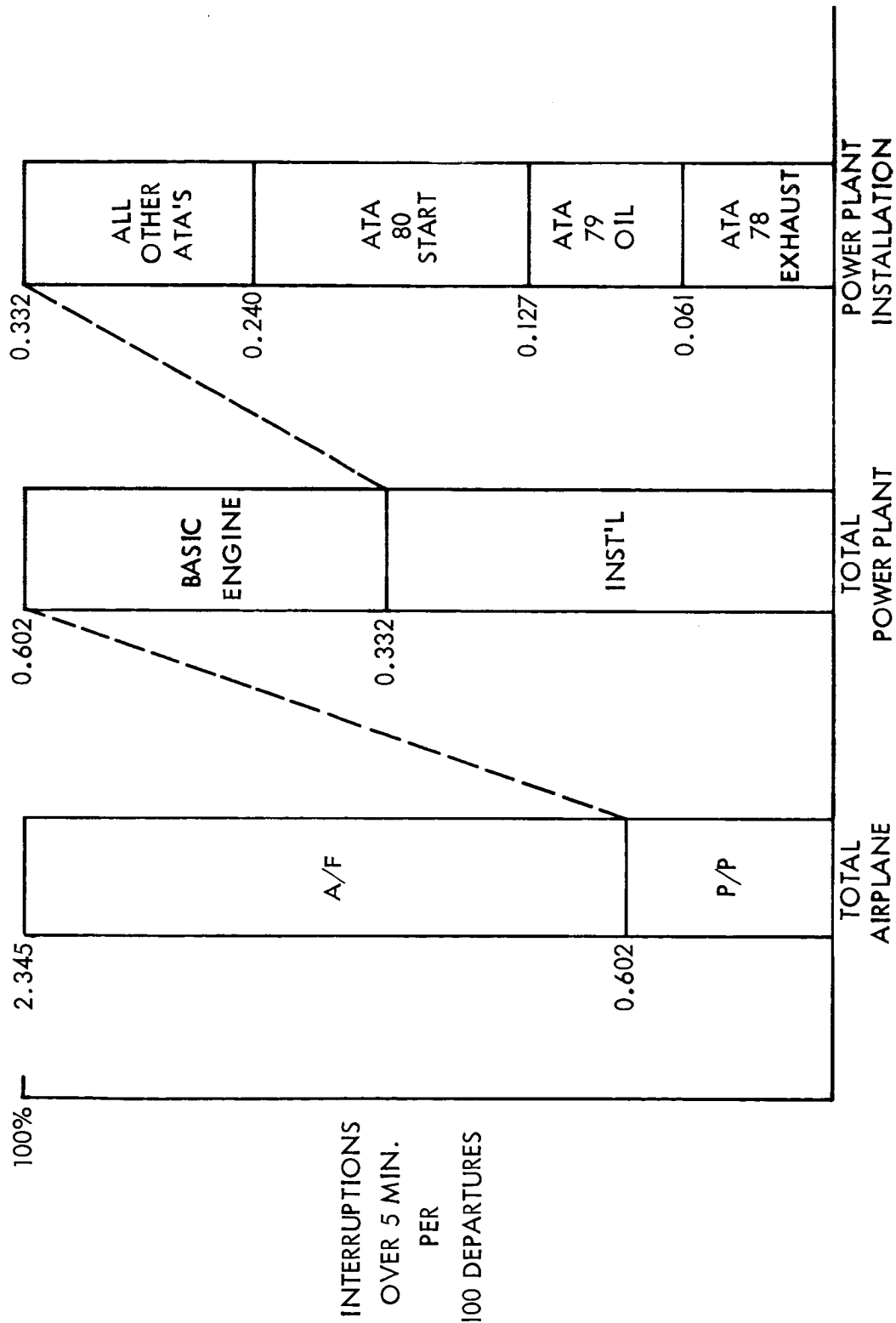


Figure III-60

727 INTERRUPTION RATE YEAR 1972

● ONE U.S. AIRLINE

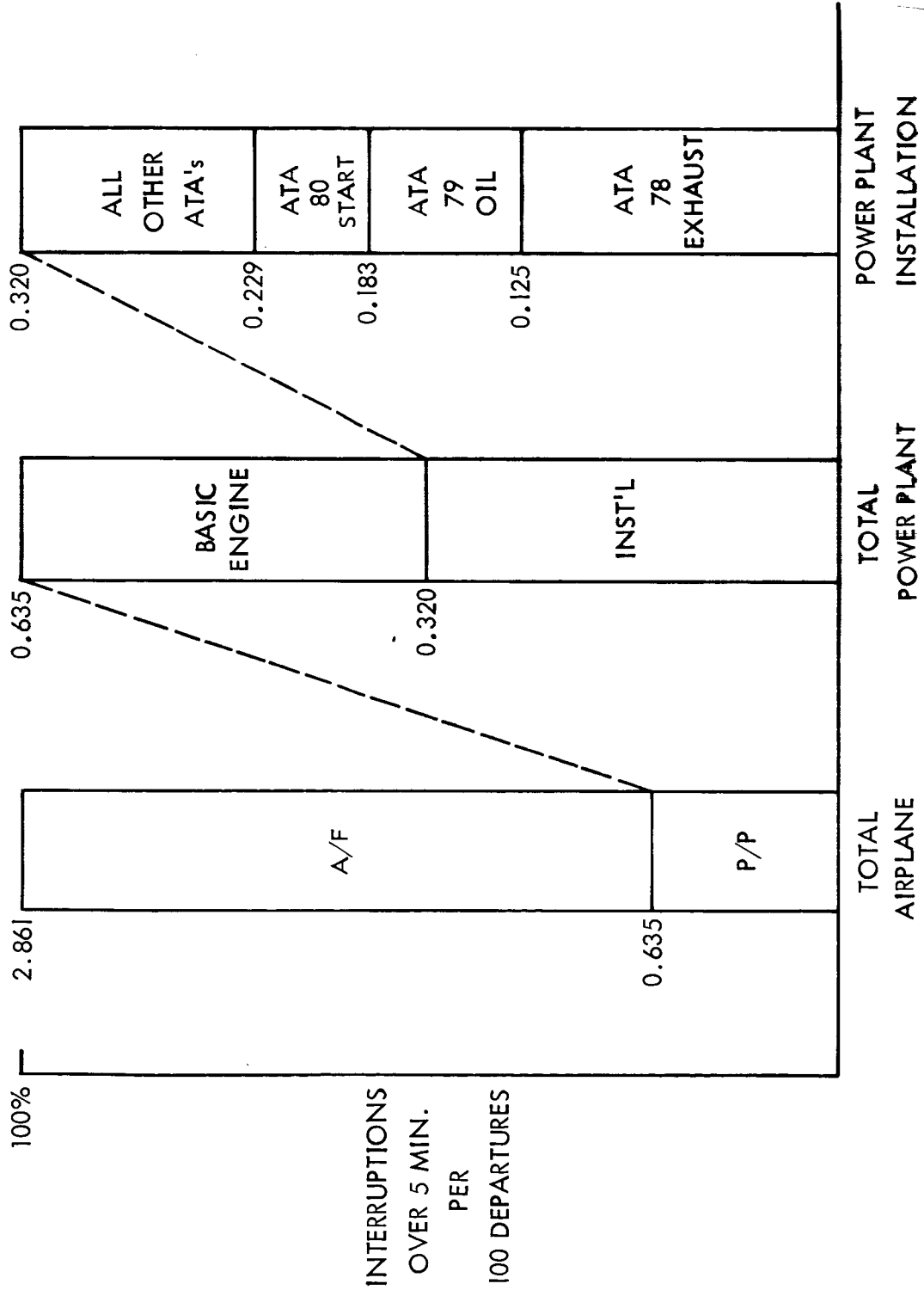


Figure III-61

737 INTERRUPTION RATE

YEAR 1972

● ONE U. S. AIRLINE

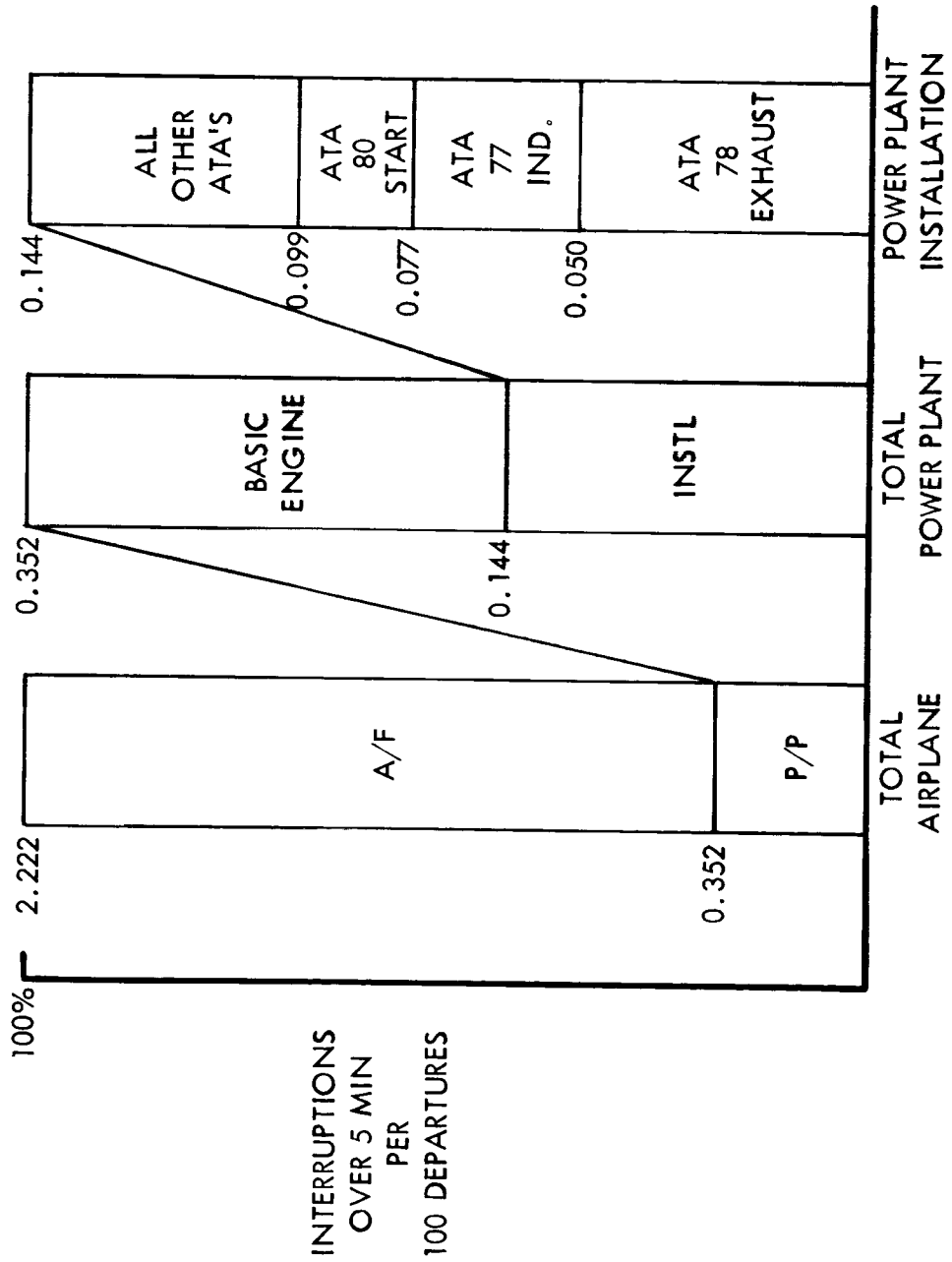


Figure III-62

4-3-74

747 INTERRUPTION RATE

YEAR 1972
(JT9D-3A)

● ONE U.S. AIRLINE

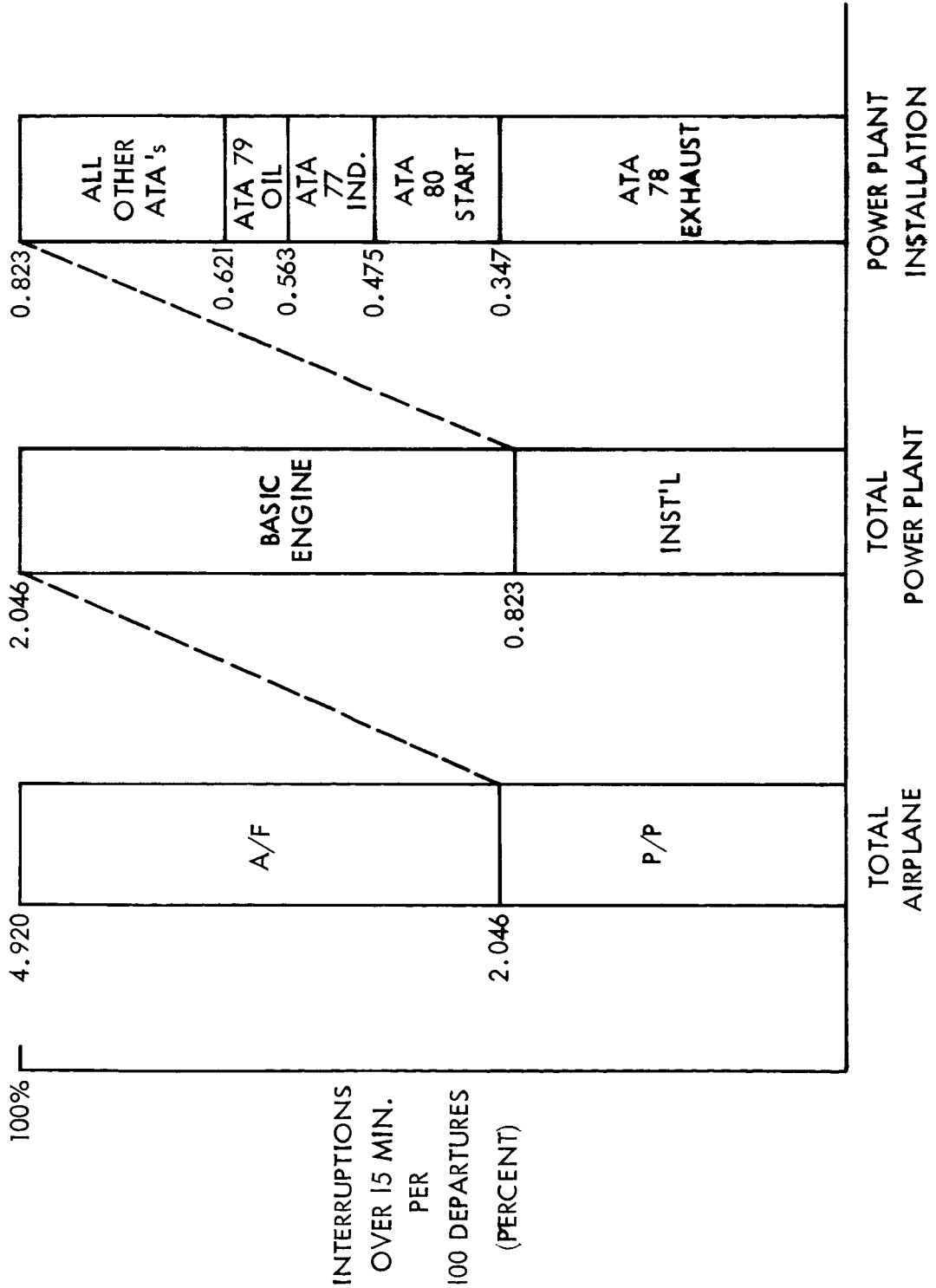


Figure III-63

POWER PLANT SYSTEMS

INTERRUPTION COSTS

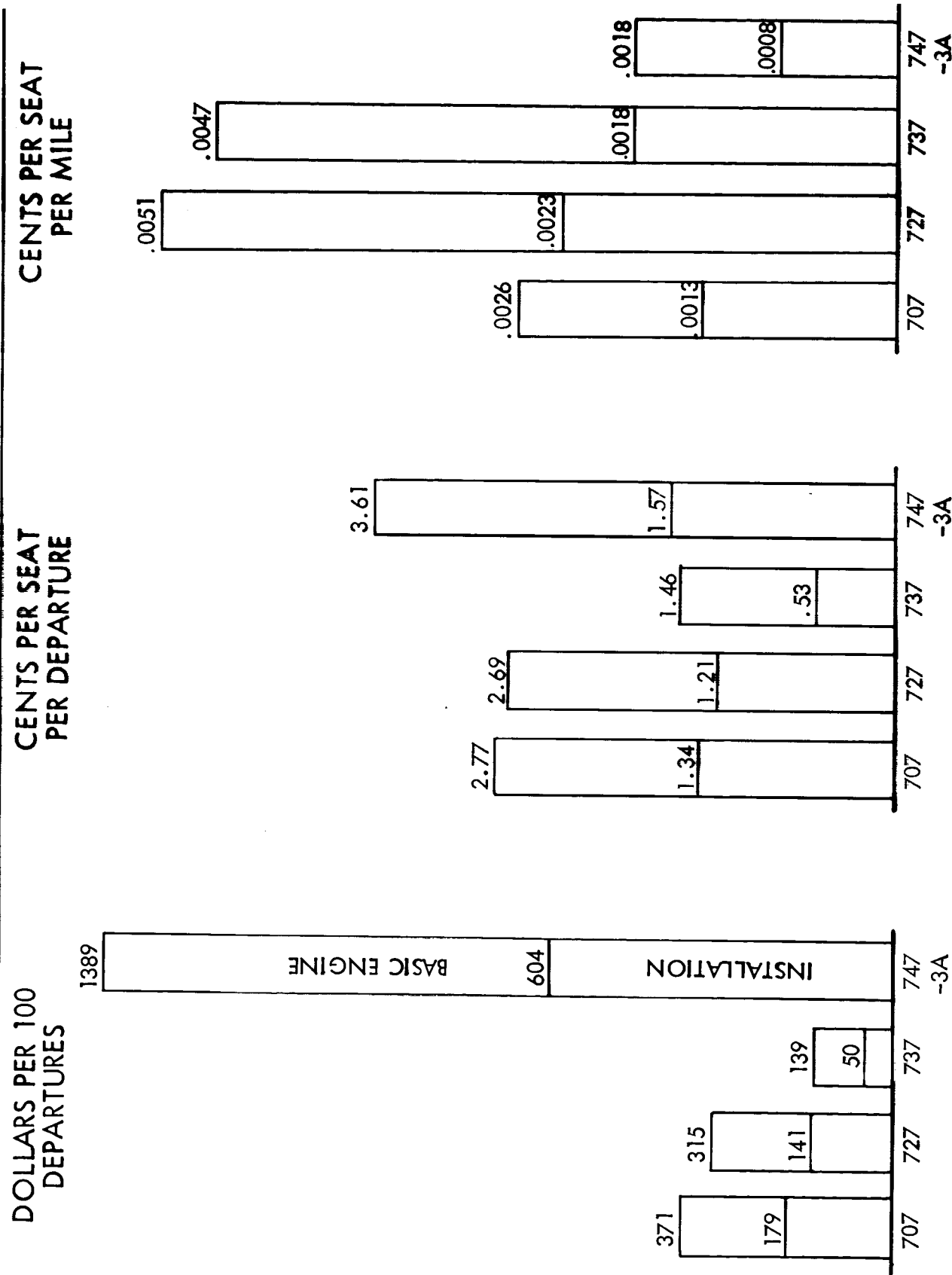


Figure III-64

707 POWER PLANT SYSTEMS

INTERRUPTION COSTS YEAR 1972

● ONE U.S. AIRLINE

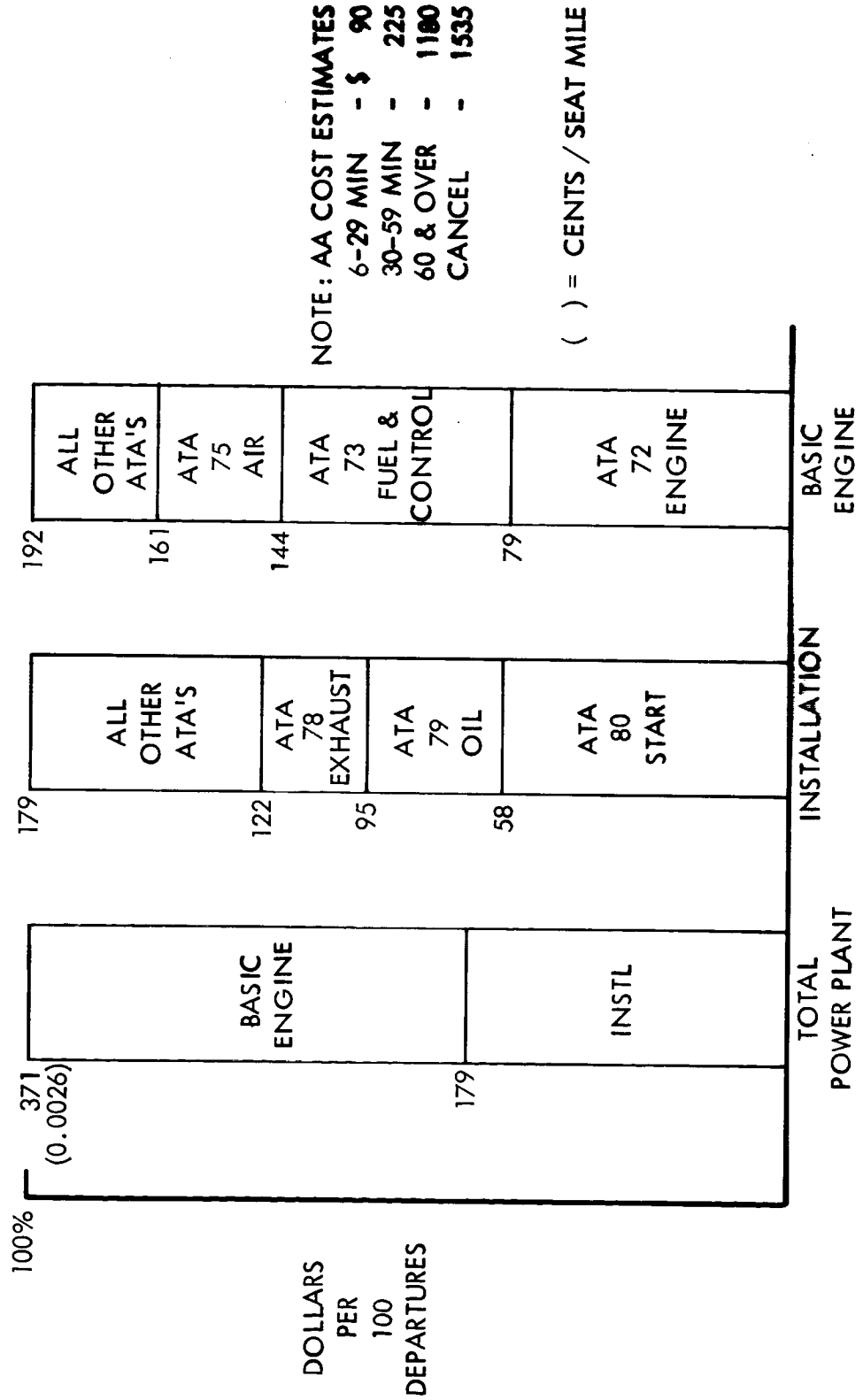
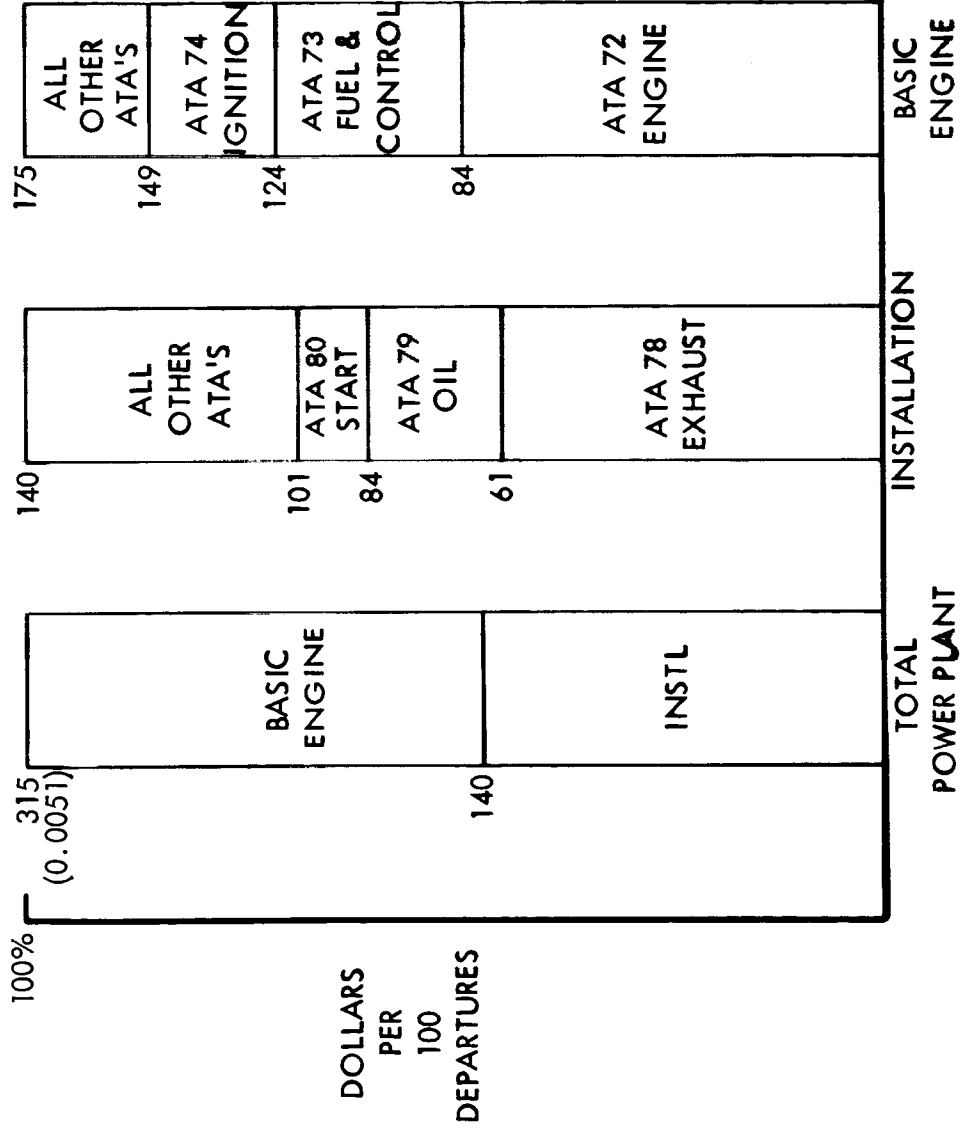


Figure III-65

727 POWER PLANT SYSTEMS

INTERRUPTION COSTS YEAR 1972

● ONE U.S. AIRLINE



NOTE: AA COST ESTIMATES

6-29 MIN - \$ 88
30-59 MIN - 218
60 & OVER - 978
CANCEL - 1272

() = CENTS / SEAT MILE

737 POWER PLANT SYSTEMS

INTERRUPTION COSTS
YEAR 1972

● ONE U.S. AIRLINE

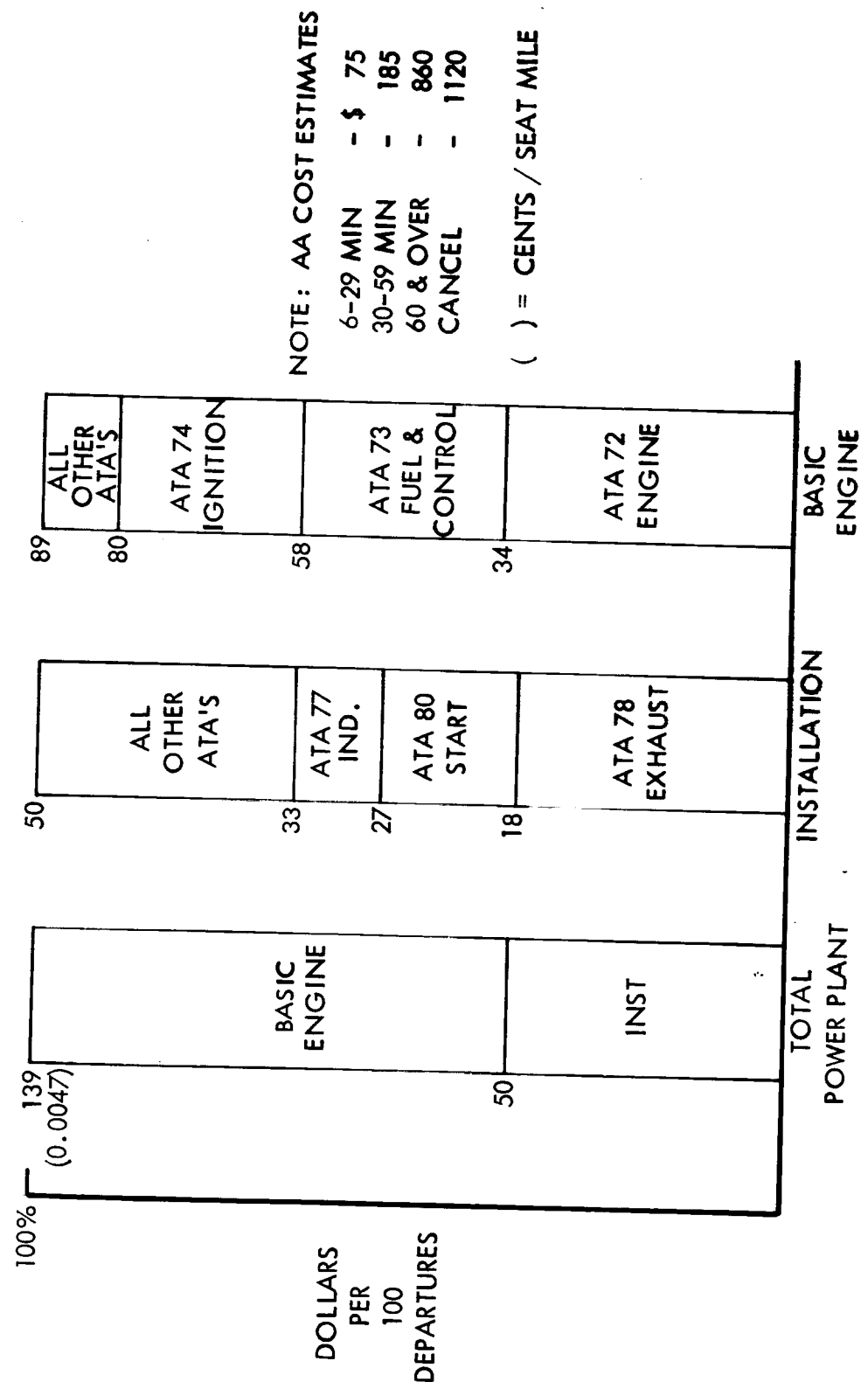


Figure III-67

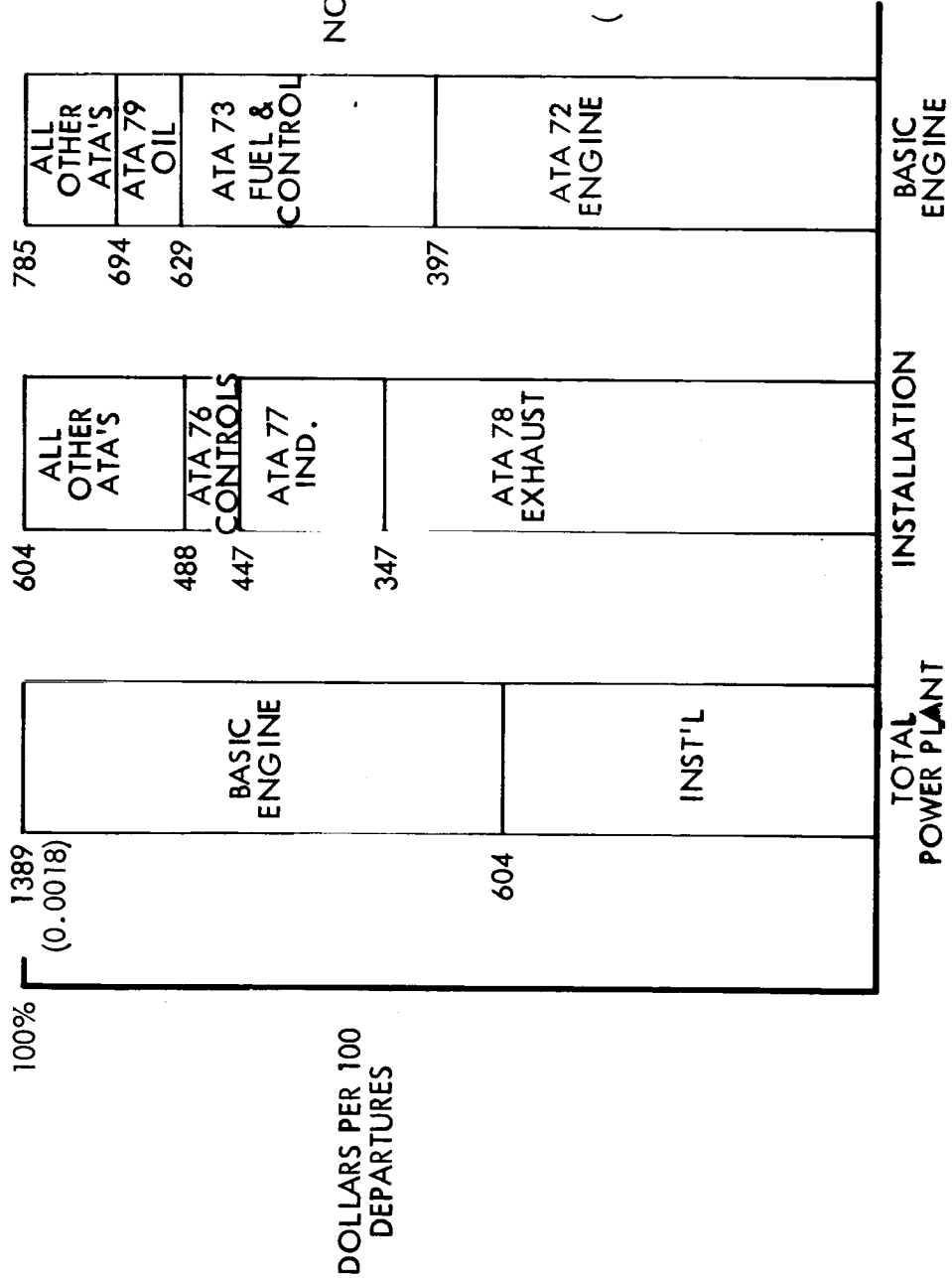
747 POWER PLANT SYSTEMS

INTERRUPTION COSTS

YEAR 1972

(JT9D-3A)

● ONE U.S. AIRLINE



NOTE : AA COST ESTIMATES

16-29 MIN - \$ 155
 30-59 MIN - 395
 60 & OVER - 1590
 CANCEL - 2065

() = CENTS / SEAT MILE

Figure III-68

IV

TASK II - ANALYSIS OF ESTIMATED OPERATING COSTS FOR A 1979
ADVANCED TECHNOLOGY ENGINE AS INSTALLED IN THE BASE LINE AIRCRAFT

A. Introduction

This section presents the results of an analysis of the estimated operating costs for an advanced 1979 subsonic transport propulsion system. Cost estimates have been prepared and presented for each of the following operating cost elements:

- Depreciation of Investment
- Fuel
- Maintenance

The base line aircraft and 1979 advanced technology engine description, operational scenario and supporting assumptions are discussed first in the subsection entitled "Background". The estimated operating cost data are then discussed starting with the depreciation of investment. The conclusions and summary presentation of results are presented last.

The purpose of this task was to utilize the economic trend data developed in Task I (Section I, II and III of this report) to estimate the operating cost impact of a 1979 advanced engine - propulsion system. A second purpose was to test the procedure of estimating engine maintenance cost from this trend data as a first step in developing an improved maintenance cost estimating methodology.

B. Background

For the purpose of this study, it was necessary to select a representative base line airplane and candidate 1979 advanced technology engine. The noise and pollution goals for the aircraft and engine were established as FAR 36 minus 10 EPNdB and the 1979 EPA emission standards for T2 class engines. The aircraft design selected as the base line is representative of a 1979 replacement for medium range aircraft. The

engine selected is a modified STF-429 study engine defined under previous NASA study programs.

The aircraft, engine and engine installation designs were selected early in this study program and prior to any real indication of Task I study conclusions. The maintenance program assumptions are consistent with those procedures in use today as discussed in Section I of this report.

1. Airplane Operational Scenario

The route structure and operational model used for assessing the operating economics of the base line airplane design is patterned after American Airlines' 727 fleet operation.

This operational model, briefly summarized in Table IV-1, is based on a 45 station network with an average flight distance of 544 statute miles. The traffic density is assumed to support 630 departures per day which can be satisfied by a 100 airplane fleet with 9.45 hours daily utilization.

There are 250 numbered flights, some of which are single segment flights although the majority are represented by a three segment flight with two 30 minute through stops followed by a typically 90 minute turn around for a new number designated trip sequence. The average airplane flies 6.3 flights a day of 1.5 hours (block time) duration. The representative flight profile is shown in Figure IV-1.

OPERATIONAL MODEL

- 100 AIRPLANE FLEET
- 45 STATIONS
 - 10 WITH FULL SERVICE AND MAINTENANCE FACILITIES
 - 30 WITH FUEL, OIL, AND LUBE ONLY
 - 5 WITH PARTIAL MAINTENANCE (TIRES, ETC.)
- 630 DEPARTURES/DAY
- 544 S.MI. AVERAGE FLIGHT LENGTH
- 1.5 BLOCK HOURS/FLIGHT (1.25 FLIGHT HOURS/FLIGHT)
- 55% LOAD FACTOR
- GROUND OPERATIONS
 - 100 OVERNIGHT STOPS AT LEAST 7 HOURS
 - 250 30 MINUTE ENROUTE STOPS
 - 180 90 MINUTE ENROUTE STOPS

FLIGHT PROFILE

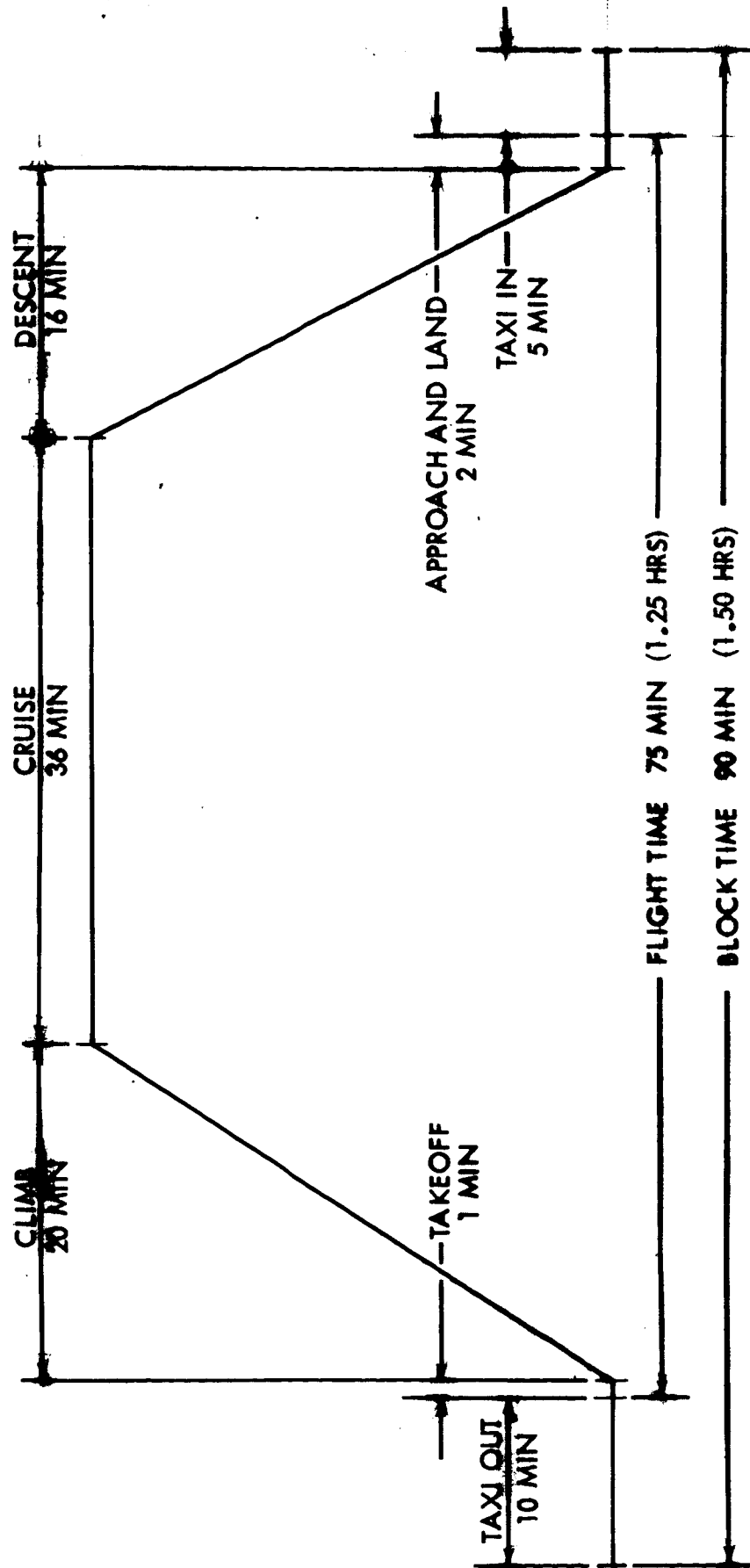


FIGURE IV-1

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2. Baseline Airplane Description

The baseline airplane configuration, Boeing Model D4-179C, is an intermediate range airplane with a double aisle body and three aft body mounted modified STF 429 turbo fan engines scaled to 22,000 pounds sea level static thrust each. The general arrangement is shown in Figure IV-2.

The body cross section is 211 inch circular which will accommodate seven abreast tourist seating. The interior capacity used as the reference standard is 24 first class passengers, 6 abreast at 38 inch seat pitch, and 157 tourist class, 7 abreast at 34 inch pitch.

The new technology wing has 2020 sq. ft. area, 25 degrees sweep of the quarter chord to minimize structural weight, and a supercritical airfoil section to account for an acceptable drag rise at $M = .84$ cruise. The wing incorporates 747 type variable camber leading edge flaps and double slotted trailing edge flaps.

The design range (maximum gross weight takeoff and 100% passenger load factor) is 1930 nautical miles at .82 Mach cruise.

The principal characteristics are listed in Table IV-2 . The weights are listed in Table IV-3.

The block time and block fuel are shown in Figure IV-3.

The sensitivity of the design to variations in the basic engine characteristics to satisfy a constant engine/payload requirement, are as follows, assuming the engine and airplane are scaleable:

IV.B.2 Baseline Airplane Description (Continued)

Engine Weight Change

A 1 pound change in basic engine weight (3 pound/ship set) will result in an 8.87 pound change in gross weight and 6.70 pound change in OEW.

A 1% change in engine weight will cause a .134% change in gross weight, a .175% change in OEW, and a .134% change in block fuel (reference Figure IV-4).

Engine Specific Fuel Consumption

A 1% change in engine specific fuel consumption will cause a .354% change in gross weight, a .157% change in OEW and a 1.06% change in block fuel (reference Figure IV -5).

Engine Geometry

A 1% change in engine diameter will cause a .084% change in gross weight (200 pounds), a .37% change in OEW (53 pounds), and a .24% change in block fuel.

A 1% change in engine length will cause a .028% change in gross weight (67 pounds), a .013% change in OEW, and an .085% change in block fuel.

MODEL D4-179C

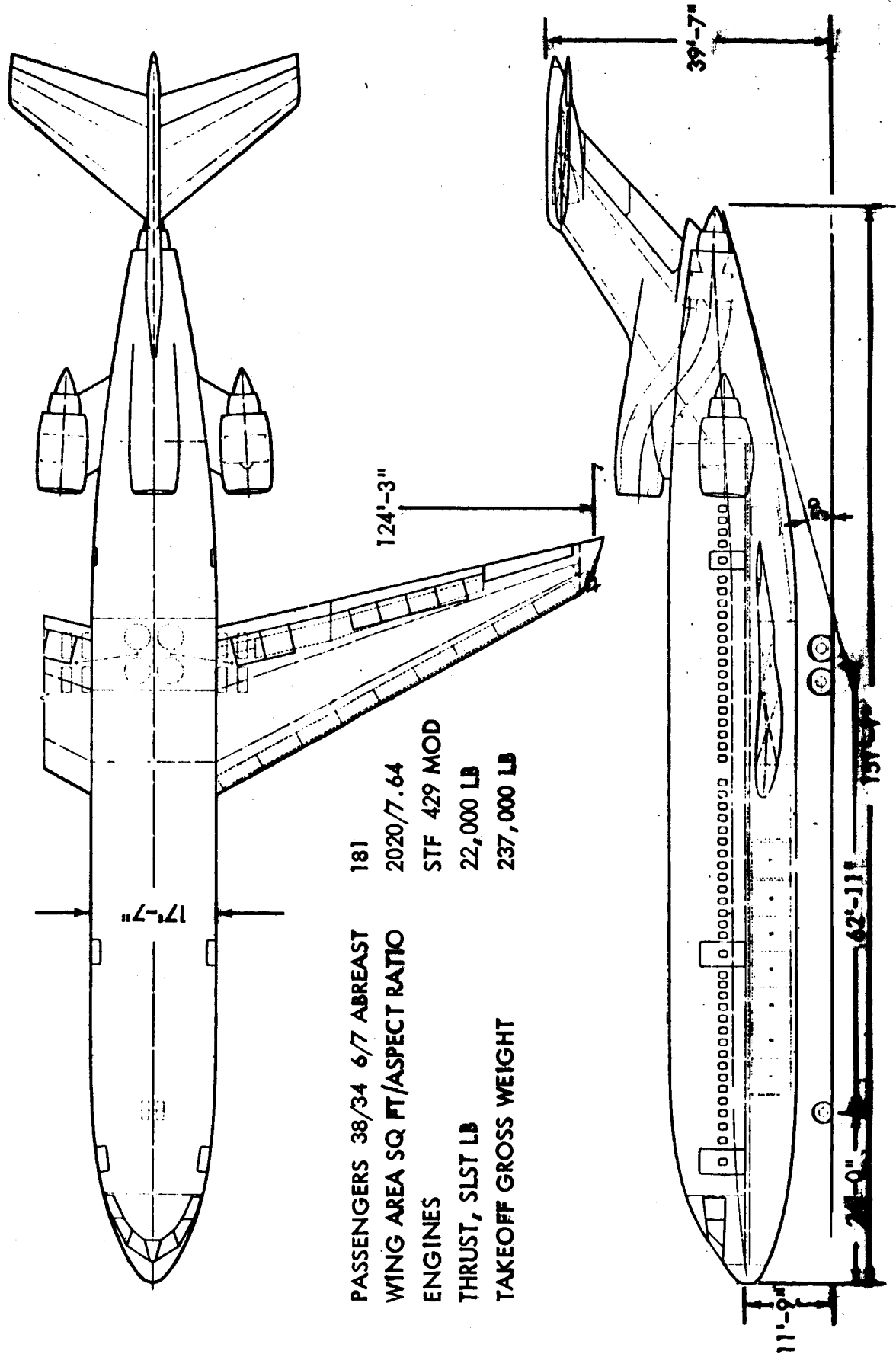


FIGURE IV-2 BASE LINE AIRPLANE CONFIGURATION

TABLE IV-2

MODEL D4-179(C) PRINCIPAL CHARACTERISTICS

Maximum Taxi Weight - lb.	238,000
Maximum Landing Weight - lb.	211,500
Zero Fuel Weight - lb.	198,000
Wing Span - ft. - in.	124' - 3"
Wing Sweep Angle at C/4	25°
Wing Area - sq. ft.	2020
Horizontal Tail Area - sq. ft.	505
Vertical Tail Area - sq. ft.	350
Overall Length - ft. - in.	171' - 10"
Body Length - ft. - in.	144" - 7" to Fan Exit
Body Width - in.	211
Body Wetted Area - sq. ft.	6947
Pass. Cabin Length - in.	1268
Number Flight Crew	3
No. of Pax. (1st Class/Tourist) All Economy	181 (24/157)
No. of Engines	(3) Modified STF 429
Engine Thrust - lb. SLST	22,000
Wheel Base - ft. - in.	62' - 11"
M.G. Track - ft. - in.	21' - 10"
M.G. Tire Diameter - in.	42 x 16
M.G. Type	Truck
Extended M.G. Length - in.	104
M.G. Truck Length - in.	56
M.G. Truck Track - in.	34
Fuel Capacity - U.S. Gal.	10,500
Range N. Mi.	1,930 @ M .82 30,000 ft.

TABLE IV-3

WEIGHT STATEMENT

MODEL D4-179C

• STRUCTURE	78,940
• PROPULSION	15,600
• ENGINES/FITTING	10,770
• ACCESSORIES	360
• CONTROLS	150
• STARTING	120
• FUEL SYSTEM	1,470
• THRUST REVERSER	2,730
• FIXED EQUIPMENT	34,420
• OPTIONS	<u>2,150</u>
• MANUFACTURER'S EMPTY WEIGHT	131,110
• STANDARD & OPERATIONAL ITEMS	<u>10,550</u>
• OPERATIONAL EMPTY WEIGHT	141,660
• MAXIMUM TAXI WEIGHT	238,000

BLOCK FUEL & BLOCK TIME

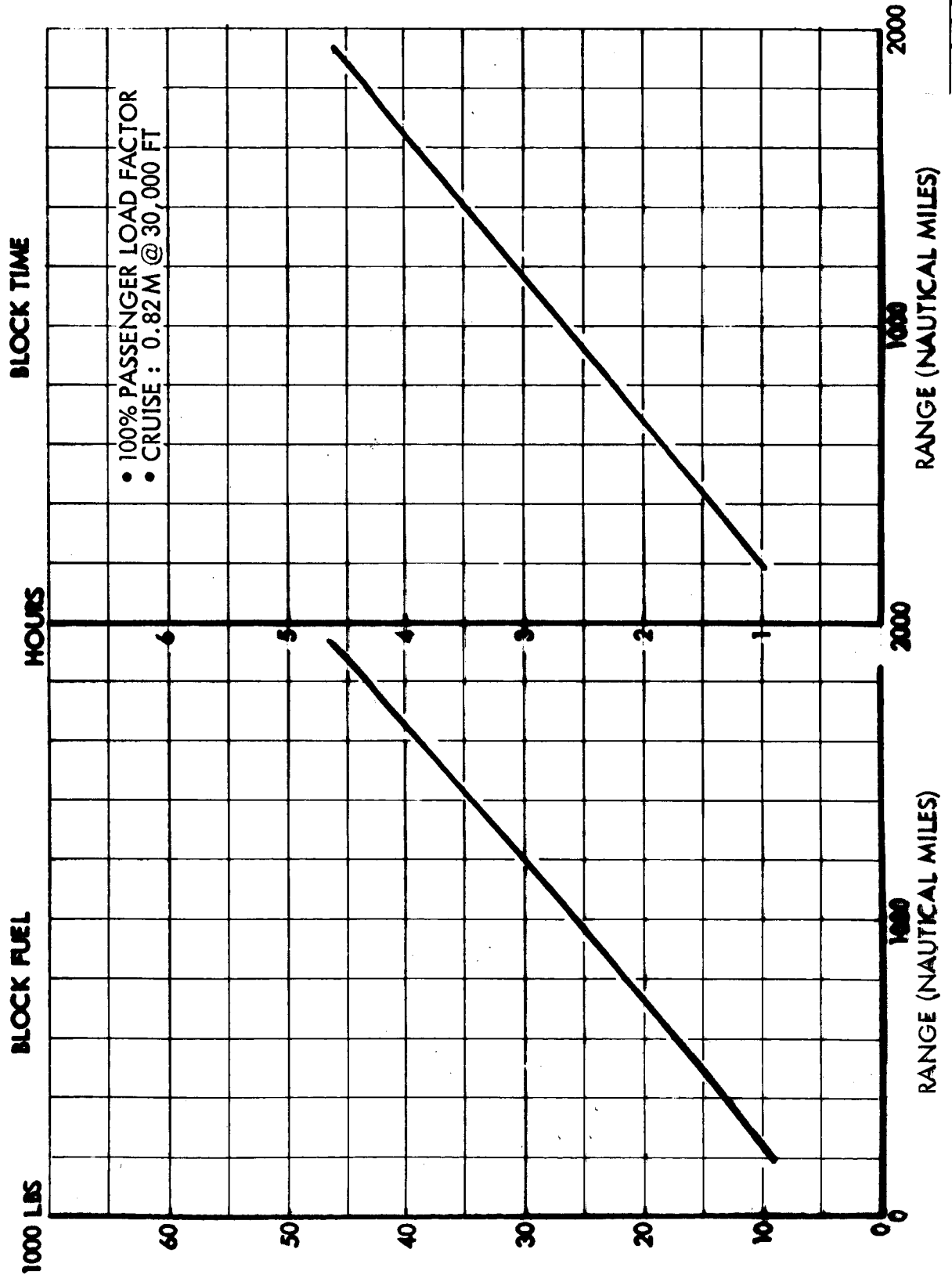


FIGURE IV-3 BLOCK FUEL & FLOCK TIME

4-4-74

AIRPLANE SENSITIVITY TO ENGINE WEIGHT

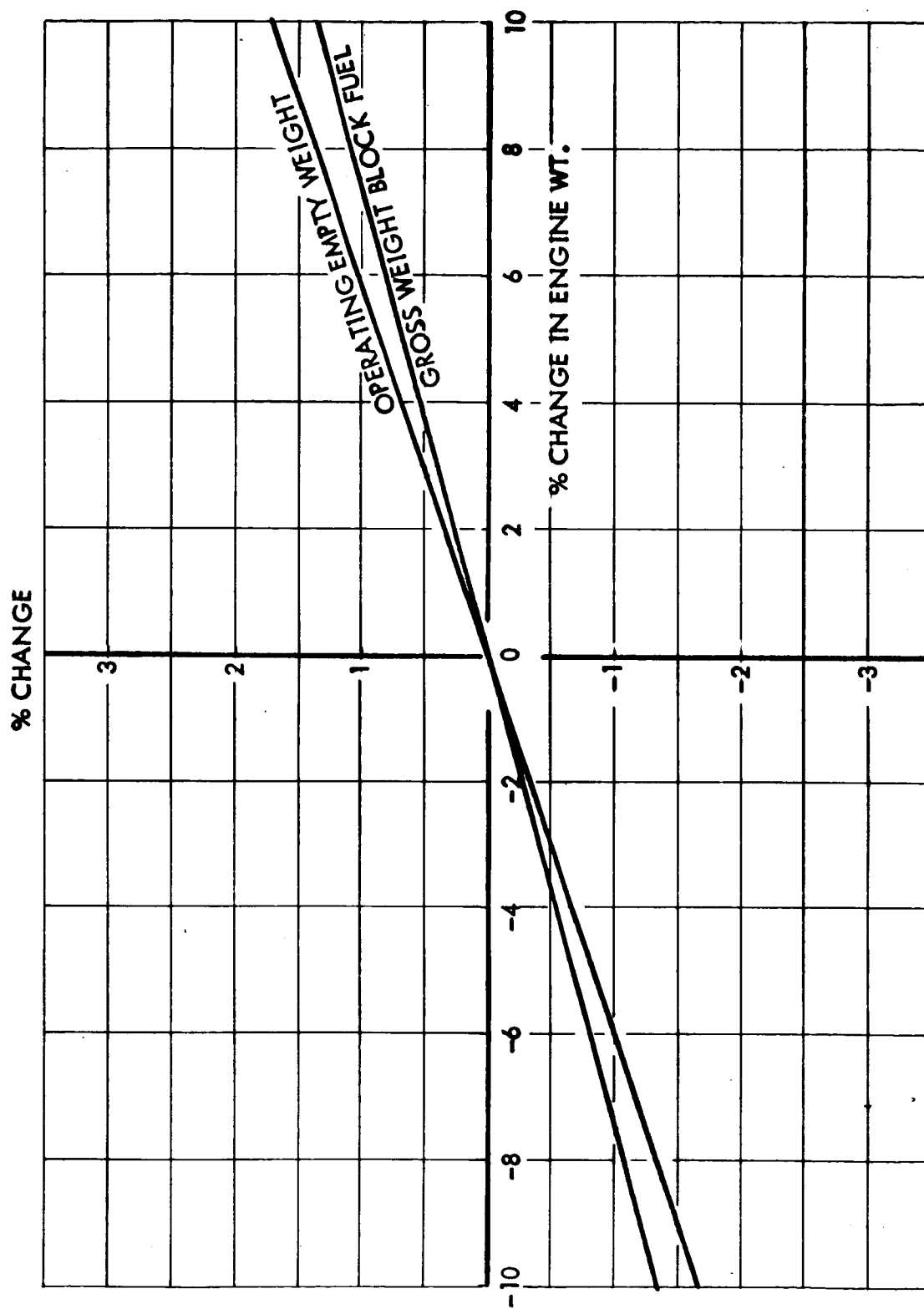


FIGURE IV-4 AIRPLANE SENSITIVITY TO ENGINE WEIGHT

AIRPLANE SENSITIVITY TO SPECIFIC FUEL CONSUMPTION

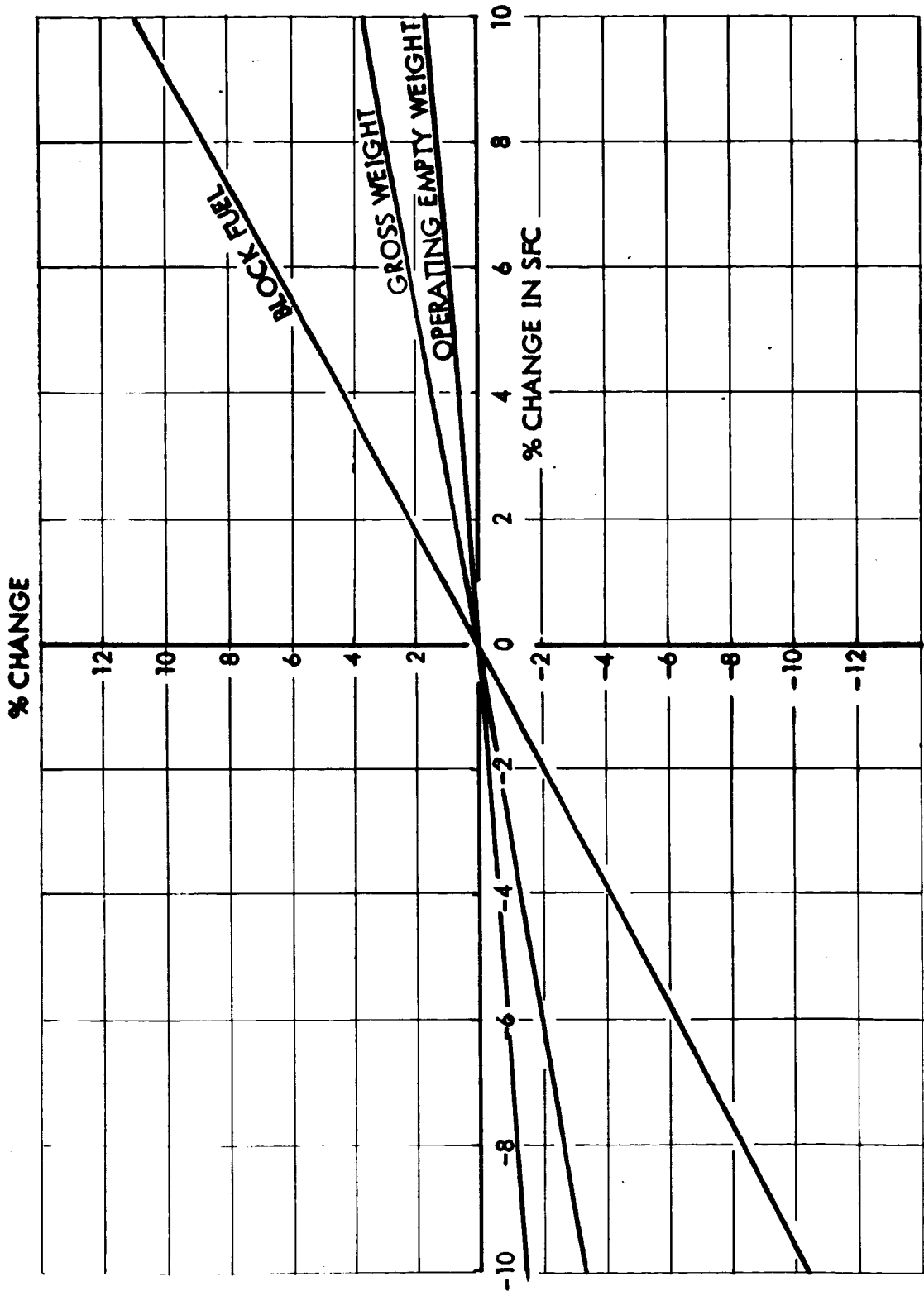


FIGURE IV-5 AIRPLANE SENSITIVITY TO SPECIFIC FUEL CONSUMPTION

3. Maintenance Philosophy

STF-429 Engine Maintenance Philosophy

During introduction of the STF-429 engine into airline operation, the following engine condition monitoring and maintenance philosophy would be applied. This program is similar to that utilized successfully during the introduction of the JT9 and CF6 engines into airline operation.

The following program also assumes that the STF-429 engine design would incorporate provisions for spectrometric oil analysis, borescope inspection, modular repair and engine performance trend monitoring, which would be developed and utilized during the engine development program

The engine maintenance program would consist of the following:

1. A minimum daily engine parameter data collection and reduction to predetermined conditions for engine health trend monitoring purposes.
2. Collection of engine oil samples at intervals of approximately 250 hours for engine oil analysis purposes to ascertain the health of oil washed parts and any deteriorating trends.
3. After a predetermined interval, as recommended by the engine manufacturer, initiate a periodic borescope inspection of hot section components; i.e. combustion chamber, nozzle guide vanes, HP and LP turbine blades, etc. These inspections would be performed at scheduled airplane maintenance lay ups.
4. Either use prematurely removed engines with sufficient operating time or schedule the removal of specific high time engines for life development purposes. It is envisaged that a maximum

sample of two engines, in conjunction with the findings during inspection monitoring of prematurely removed engines, will provide enough data to determine the needs (task and frequency) of an engine condition monitoring program.

5. Establish the engine on a condition monitored maintenance program. Removals would be predicated upon deterioration trend indications, expiration of life limited parts times/cycles and incorporation of modifications and upgrades.

b. Aircraft Maintenance Philosophy

Through-Flight Service

This service is performed prior to airplane dispatch from an enroute station. It is the shortest time service accomplished on an airplane as part of its flight operations. Partial offloading and onloading of baggage, cargo, and passengers is accomplished, passenger service accommodations may be checked and tidied, any non-deferrable maintenance is completed, and ground equipment available for starting and other functions is cleared of the airplane prior to dispatch. Power plant cowling is not opened during this check but may be opened to complete non-deferrable maintenance.

Turnaround Service

This service is performed at terminating locations in the flight route structure. It consists of a visual check of the airplane exterior with particular attention to indications of fuel or oil leaks, obvious discrepancies such as worn or flat tires, low shock struts, fuselage or wing damage, servicing check of the oil supplies, check of exterior lighting, check and servicing of cabin galleys, water system, lavatories, oxygen system, and servicing of fuel. Interior tidying is accomplished, depending upon need and available ground time. As a minimum, malfunctions affecting airworthiness are repaired, and at stations involving a long turnaround or over-nighting where men and equipment are available additional unscheduled and scheduled maintenance is sometimes accomplished.

"A" Check

A typical "A" check is performed at scheduled time intervals for the airplane and is normally accomplished at the larger stations in the route structure or at the main maintenance base. This check includes a walk-around service.

It further includes the opening of access panels to check and service certain items of equipment which are scheduled at this time interval. Passenger service requirements are accomplished, depending upon need. Malfunctions affecting airworthiness are repaired. Other maintenance which is outstanding is performed, depending on the time available.

Phase Check

A typical phase check provides for a thorough visual inspection of specified areas, components and systems as well as operational or functional checks of specified components and systems. Each check includes the requirements of traditional "A" checks, multiple "A" check work items and portions of "C" and "D" checks at suitable intervals. These phased intervals might vary anywhere from 200 to 800 hours depending upon the work packaging plan and other airline operating variables. Special fractional portions of the structural check requirements are often also performed during the phase checks. Unscheduled maintenance requirements revealed by the check as well as deferred maintenance will be accomplished at this check interval.



Structural Check

This check includes the scheduled phase check work package plus, on a sample of the fleet, the detailed structural inspection work packages not previously inspected as part of the phase checks.

Check Schedule

The assumed scheduled check frequency and the elapsed time requirements and objectives for checks, lubrication, deferrable maintenance and incorporation of service bulletins are shown in Table IV-4

NOTE: "C" and "D" check descriptions are contained in section 5B of referenced document D6-15198, "Maintainability Design Guide".

SERVICES AND CHECKS	ASSUMED CREW SIZE	1 	2 	MAXIMUM ELAPSED TIME	
				REQUIREMENT	OBJECTIVE
Through Flight	1		Per Flight Schedule	30 Min.	25 Min.
Turnaround	2		New Flight Origination	90 Min.	90 Min.
"A"	10		125 Flight Hours	3 Hours	2 Hours
Phase	40		750 Flight Hours	16 Hours	12 Hours
Structural	50		16,000 Flight Hours	120 Hours	72 Hours

1 

For gaining access, checking conditions, non-routine maintenance and closing up. Service Bulletin incorporation not included in assumed crew sizes at elapsed time.

2 

Upon introduction into service based on 727 and 747 experience.

SCHEDULED MAINTENANCE CHECK ASSUMPTIONS

FIGURE IV-4

4. STF 429 Engine Description

The STF-429 is a twin spool, fan-high unaugmented turbofan designed to operate with separate, fixed primary and fan exhaust nozzles. The technology level for the STF-429 engine is consistent with a 1979 certification date.

The engine was originally sized to produce 40,000 lbs. of uninstalled take-off rated thrust during sea level static standard day operation. For this study it has been scaled to 22,000 lb. thrust size. The scaled engine weight is 3590 lbs.

The STF-429 cycle was selected to meet a noise goal of FAR Part 36 minus 10 EPNL and to have low emission levels. The engine has a bypass ratio (BPR) of 4.5:1 and a 2.0:1 fan pressure ratio. The overall pressure ratio (OPR) is 25:1, the maximum burner exit temperature is about 2700°F (take-off thrust is flat-rated to an ambient temperature of 90°F at 1000 ft. alt.).

Fan

The fan is a low tip speed, two-stage design with extensive axial spacing between airfoil rows for low noise. The fan blades are composite material and are unshrouded.

Compressor

The compressor is a ten-stage, constant mean diameter configuration with a drum rotor and cantilevered stators. The inlet guide vanes and the first two stator rows are variable.

Burner

The burner is a two-zone, piloted premix configuration designed to reduce both high and low power emissions. The burner liner uses FinwallTM material to reduce the liner cooling requirement and improve the burner exit temperature profile.

Turbine

The high pressure turbine is a two-stage design, with the blades and vanes of both stages air cooled. The blades are unshrouded. Segmented, thermal response tip seals are used with both stages to maintain tight clearances over the blade tips.

The fan drive turbine comprises four stages, close coupled to the high pressure turbine. The fan drive turbine has a relatively high loading because of the low rotational speed of the two stage fan.

Fuel and Engine Control System

Engine control is accomplished by a combination electronic-hydraulic, closed loop system. This system provides accurate thrust scheduling and protection against engine overspeed and over temperature with a minimum of flight crew attention.

Engine Maintainability

The engine design includes such features as modular construction, provisions for borescope, radioisotope and sonic inspection and provisions for on-wing replacement of key components and modules.

STF 429

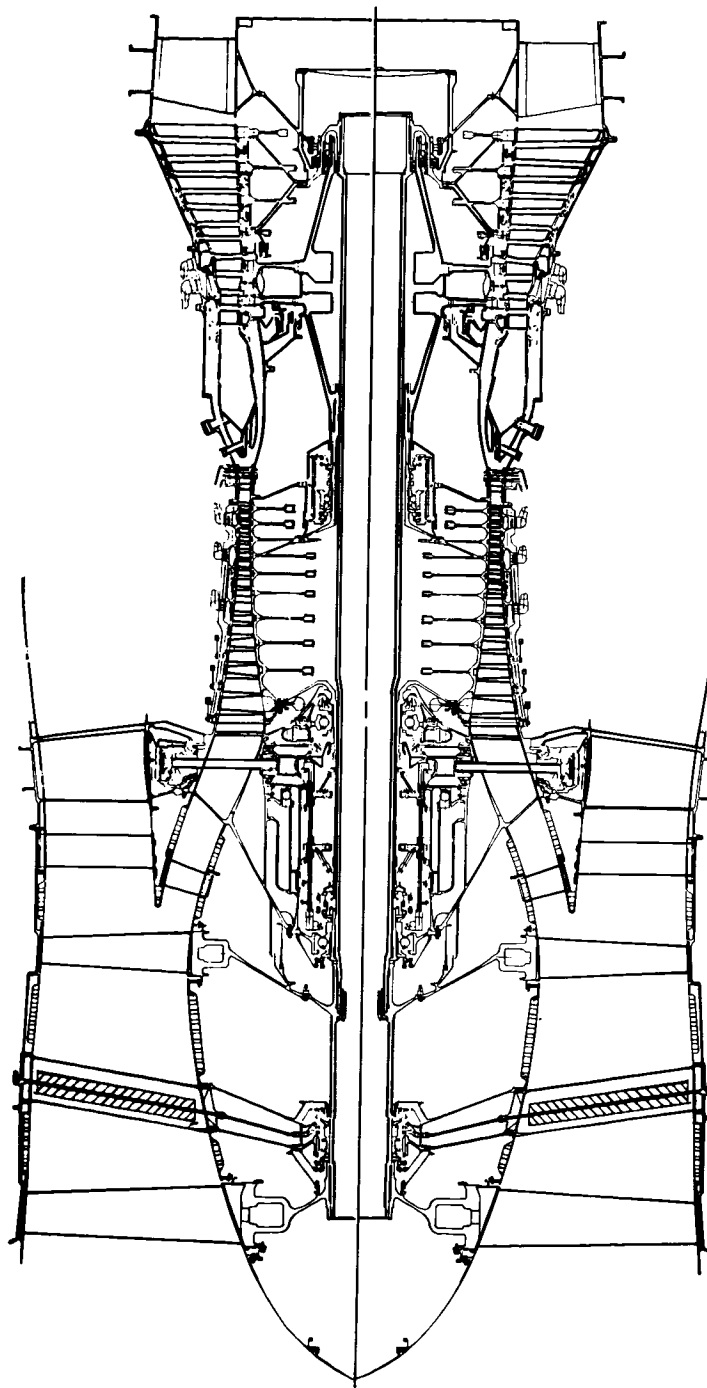


FIGURE - IV-6 STF-429 ENGINE CONFIGURATION

POWER PLANT INSTALLATION

General

Three modified P & W STF 429 engines are installed as shown in Figure IV-2. The fuselage mounted engine installation will be discussed in detail below.

Engine Mounting

The engine is mounted from a horizontal strut as illustrated in Figure IV-7. Vibration isolator shock mounts have been used to reduce fuselage vibration and noise.

The engine attachment is accessible by opening the fan case and fan duct core cowls. Cone bolt studs have been used for ease of alignment and reduced fastening time.

Cowling

The fan case cowling is made in three aluminum honeycomb sections. The upper section is hinged inboard at the strut and the lower half consists of two sections swinging inboard and outboard for easy access to fan case mounted accessories.

The fan duct cowling assembly is bifurcated into three sections and includes the fan thrust reverser. The upper half (180°) is hinged up from the upper strut. The two lower sections hinge down to provide access to the core mounted accessories. On engine removal only the outer lower duct section must be removed. The three duct sections are power actuated or manually cranked open and closed with linear actuators also acting as stay braces.

The three quarter length bifurcated fan ducts are sized to contain 1.20" thick aluminum honeycomb acoustic lining on the inner and outer duct walls. The circumferential splitter is positioned forward of the reverser blocker

ENGINE INSTALLATION

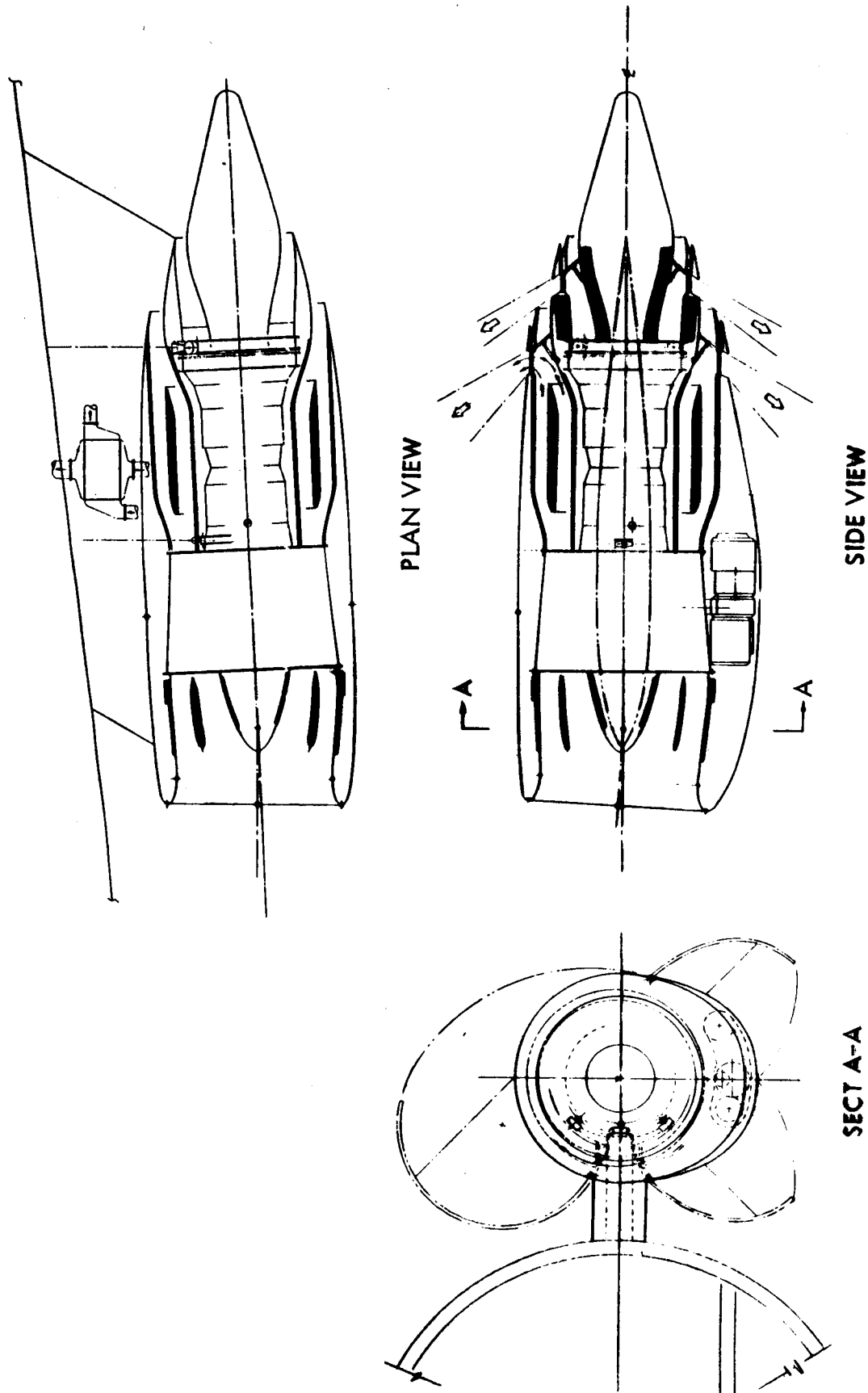


FIGURE IV-7 ENGINE INSTALLATION

11-27-73

doors to optimize its length and provide adequate duct flow area. It is acoustically lined on both sides with aluminum honeycomb having a total thickness of 2.40" by 30.0" long. The outer fan duct cowl skin is of aluminum frame and stringer construction, structurally attached to the duct.

d. Inlet

The aluminum inlet is bolted to the engine fan case flange using 12 bolts.

The inlet is acoustically treated with aluminum honeycomb along its outer wall and has a treated ring and rotating spinner. Access for repair and replacement of fan blades can be gained by removing the spinner.

Hot air deicing ducts are routed within the leading edges of the inlet, ring and struts. The hot air is bled off the engine compressor, sprayed against the inner side of the leading edge surfaces and released into the engine inlet.

e. Fan Thrust Reverser

The fan reverser has been located aft of the circumferential acoustic splitter to provide maximum treatment in the fan duct and take advantage of noise attenuation while in the reversed thrust mode.

The blocker doors and cascade turning vane cover panels are translated along roller tracks adjacent to each cascade and powered by screw-jack cables driven from a master hydraulic actuator located in the strut bifurcation. The fourteen fan duct blocker doors are divided as follows:

- a) Seven blocker doors and five turning vane sections on the upper duct;
- b) Three blocker doors and two turning vanes in the inner lower duct;
- c) Four blocker doors and three turning vanes in the lower outer duct.

The blocker door fan air thrust loads are carried into the inner fan duct wall by its pivoted drag link. The outer wall carries the track and turning vane loads which are in turn reacted at the inner and outer fan case flanges, respectively.

f. Primary Duct and Thrust Reverser

The primary nozzle, plug and thrust reverser assembly is bolted to the engine's aft flange. The exhaust plug is supported by four internal struts forward of its thrust reverser blocker doors. During engine removal the exhaust nozzle assembly may remain on the airplane by being supported from a strut mounted aft translating track system.

The plug and forward nozzle duct are acoustically lined with 4.0" thick inconel honeycomb lining.

The primary thrust reverser components, actuation system and load paths are typical to the fan air thrust reverser system.

g. Engine Removal

For removal the engine is lowered from the strut using an overhead crane or forklift platform. Interconnections from the engine to airplane are broken at the strut to Nacelle line and are accessible when the fan case and bifurcated fan duct cowls are opened.

Accessory driven and engine mounted components are removed with the engine. The inlet is transferred to the new engine.

h. Systems

Pre-cooler, associated bleed ducting and system plumbing are contained in the strut. A bifurcation through the fan duct contains the systems and ducting to the engine core.

i. Accessories

The accessories (starter, hydraulic pump, IDG, lubrication and scavenge pumps, fuel control and fuel pump) are mounted on an engine-driven gear box located below the engine fan case.

j. Servicing

Separate access panels are provided for servicing the engine and IDG oil tanks, reading oil quantities, and for starter valve override.

C. OPERATING ECONOMICS/COSTS

1. Introduction

Of the costs typically classified as airplane direct operating costs, three are directly dependent upon propulsion system performance, design, reliability and price: depreciation of investment (acquisition costs), fuel consumption costs, and propulsion system maintenance costs.

a. Depreciation of Investment or Acquisition Costs

The following items are part of the acquisition costs of a new aircraft propulsion system:

1. That part of the aircraft purchase price specifically due to the selected propulsion system. The purchase price of the engine and its power plant package, i.e. inlet, reversers, plumbing etc. make up these costs.
2. The spare engines, spare engine build-up units (QEC's) spare engine modules and initial pool of spare parts required for on-site spares and in process pool for rework.
3. Facilities or the investment into fixed overhaul/repair floor space and test cells required for maintenance of the propulsion system.
4. Special tooling required in the rework, repair, transportation and testing of the propulsion system.

All of these expenses are involved in the purchase of a new aircraft and engine type. The purchase of these materials is accomplished using both equity capital and borrowed capital. Whether the

capital is borrowed or equity, the cost of capital for analysis purposes is treated as a cost at a rate of interest of 12.5% after taxes to provide a return on investment. The cost of capital will not be considered; but should be added in determining overall economic impact of specific propulsion system alternatives. These investments, new engines, spares, facilities, and tooling costs are written off over a period of time. The latest average airline schedule for depreciation of investments is 14 years to 10%. Not all of the items discussed above are depreciated in the direct operating cost portion of the airplane direct operating cost. The facilities and tooling expenses for the engine are depreciated against estimated aircraft operating hours over a 14 year period in the indirect operating cost categories of group equipment. The purchase price and initial spares are covered in direct operating cost and amount to roughly 7% of the 1979 aircrafts' direct operating cost. The detailed estimates of these costs and supporting information follow this general introduction.

b. Fuel Costs

Fuel costs are based on estimated fuel burned by the engines for a given flight segment. The fuel costs have, of course, become more important in the recent past with increases of 200% to 300% in the price of fuel being typical. For the purpose of the study, a fixed price of 18 cents per gallon was picked and the impact of variations in fuel price was addressed parametrically. At the assumed price, fuel represented approximately 23% (\$324.45/F.H.) of the direct operating cost for the average mission. Again a more detailed explanation of this cost element follows in later sections.

c. Maintenance Costs

The propulsion system maintenance cost elements including labor, material and outside services (O.S.S.) have been estimated on the basis of the line and shop work involved in maintaining the power plant described in the section IV B.3. Two phases of engine/propulsion system evolution will be addressed. The "mature phase" will be addressed first and the introductory phase second.

2. Depreciation of Investment

The various cost elements which make up the investment base are addressed in this section. The individual cost estimates were all prepared in terms of 1972 year dollars and on the most realistic basis possible.

a. Purchase Price of Aircraft and Installed Engines

For the purpose of this study, the price of the base line aircraft was established for a breakeven quantity of 250 units. This breakeven point, the price for the number of units sold which will recover the non-recurring expenses involved in the development and certification of the aircraft, is representative for future commercial programs.

The estimated sales price for the base line aircraft less basic engines on this basis is \$11,600,000 - 1972 dollars. The actual purchase and delivery of the fleet of aircraft to an airline would be spread over a considerable period of time. The delivery schedule selected for the representative aircraft fleet was established as 12 airplanes the first year and two per month (24 per year) thereafter until the total of the 100 airplanes are delivered. This corresponds to introduction of the entire fleet over a 56

month period.

The engine price was estimated to be \$1,050,000 - 1972 dollars on a comparable basis.

The power plant installation portion of the airframe price is \$1,290,000 for the three installation positions, of which \$318,000 is attributable to the nacelles and \$972,000 to the reversers and other subsystems and accessories.

The price of the complete aircraft is therefore \$14,750,000 - 1972 dollars and the propulsion system represents 30.1% of the flyaway aircraft price. The advanced propulsion system represents a much larger portion of the total aircraft price than for previous aircraft. This increase is due to the additional cost associated with both engine and installation to meet the stringent noise requirements. Additionally, the relative engine cost is increased due to the composite fan and very high temperature turbine which requires expensive cooled turbine blades, nozzles and case design.

b. Power Plant Spares Support Investment

Power Plant spares support required for the operation of an airline fleet includes complete power plants ready to attach to the airplane at the one extreme and nuts/bolts required for the repair of an accessory at the other. The determination of what units are provided as spares and the level of investment varies from airline to airline. Each airline analyzes the unique factors with which its operation must cope and optimizes spares support accordingly. The following paragraphs discuss power plant spares support requirements in two principle categories, namely; that necessary to meet the airplane's needs on an hour by hour basis and that required to process the power plants through their repair cycles.

The major power plant spares investment is in flight equipment held in readiness as insurance that an airplane will not be kept out of service unduly for want of a replacement unit. The most costly of these is obviously the complete power plant. Also, a variety of lesser units is normally provided. These include such items as:

- . engine modules - if the airline has elected to set up field station module exchange capability.
- . engine components such as fuel controls, fuel pumps, fuel nozzles, bleed valves and thermocouples.
- . installation components such as thrust reversers, cowl panels, coolers and controls.
- . engine driven airplane accessories such as generators, constant speed drives and hydraulic pumps.

The quantity of the flight equipment spares to support a mature fleet (and hence the capital investment) is sensitive to various factors inherent in the operation. Some of the more significant of these are as follows:

- . fleet size, engine hours flown and geographical route structure.
- . total engine (and component/accessory) removal rates at any point in time.
- . shipping time between the repair shop and the stations where replacements are made.

A number of trade-offs are available to airline management which can reduce the spares support investment if the corresponding compromises can be accepted:

Reduced Spares Option

Compromise

- | | |
|---|---|
| . Spares pooling with other airlines. | Possible non-availability due to prior use by another participant. |
| . Ferry flight with one engine inoperative to centralized stations where spares are concentrated. | Reduced flight safety margins, loss of revenue for the flight segments. |
| . Sophisticated monitoring of flight equipment to detect impending malfunction and to enable routing the airplane for correction. | Higher investment in equipment and personnel. |
| . Decreased transportation time. | Higher costs, difficulty of carrying 747/DC10 size power packages in current airfreighters. |

Reduced Spares Option

- . Decreased shop processing time.
- . Rapid incorporation of manufacturer's service bulletins and upgrades.
- . Arbitrary reduction of spares quantities.

Compromise

Shop capacity costs escalate rapidly beyond the optimum point.

Risk that modifications early in the program will be only partially effective requiring further expenditures for redo, airplanes out of service possibility.

Increased risk of non-availability of replacement units resulting in high costs for airplanes out of service.

The options available to the airlines constitute various ways of "living with" the power plant problems. Obviously, the manufacturers' role is to ensure that all possible deficiencies are corrected during the development program and that effective corrections for the residual problems are provided expeditiously.

The power plant spares investment level for a new fleet at the beginning of operation is different from what it will be when the fleet matures. By scheduling spares deliveries early in the program, a high ratio of spares to flight units can be made available to assure uninterrupted flight schedules while coping with unanticipated problems. As the quantity of flight equipment increases, the spares quantities must also increase but having started at a higher level

the ratio can be allowed to decrease. However, experience shows that the peak spares demand is very likely to require a higher investment than the mature fleet level. The airline has several options available for managing this situation, such as:

- . leasing the peak demand excess power plants from the manufacturers.
- . purchasing the later delivery airplanes less power plants and equipping them with the units in excess of mature level requirements.
- . converting the excess to subassemblies and/or parts and utilizing them to support the repair shop requirements.

The option or combinations of options selected is based upon the most cost effective for the conditions confronting the individual airline. Also, the situation must be carefully managed to make appropriate adjustments as experience is accumulated.

The foregoing paragraphs have dealt with the spares investment levels required to support the routine flight operation. The other significant spares category is that required to support power plant equipment in process of repair. These spares, referred to as shop spares, are in excess of that required to build the number of power plants in process of repair at any given time. Shop spares are allocated as follows:

- . new or serviceable "shelf" stock held in readiness to replenish scrap quantities.
- . parts in the "pipelines" to support the production flows through the various repair processes.
- . expendable material consumed each time a unit is disassembled and reassembled.

- potentially repairable parts held for the development of a repair.
- **serviceable parts, subassemblies and modules in the shop "pool"** - used to shorten the in-process time of higher assemblies.

The magnitude of this investment is sensitive to the quantity of power plants supported, the in-process times of the various repair cycles, whether the work is done in-house or contracted out and the **rapidity with which repairs are developed.**

The overall power plant spares investment represents a major factor in airline economics. For this reason it commands close management attention and is under continual review to enable rapid response to changes in the multitude of interacting factors affecting both demand and supply.

1. STF-429 Power Plant Spares Support

A study of the power plant spares requirements was conducted based upon the D4-179C/STF429 Fleet Operational Model. Several simplifying assumptions were made regarding airplane deliveries, entries into service, daily utilization, removal rate averages for the early years of operation, etc. Nevertheless, it applies actual airline experience to the determination of spares investment levels to support the hypothetical fleet.

The assumptions used in the study were set down as ground rules.

Table IV-5 lists these ground rules.

TABLE IV- 5

STF-429 Power Plant Spares Support

Ground Rules

1. Airplane Delivery Schedule

<u>Year</u>	<u>Year In Service</u>	<u>Rate Per Month</u>	<u>Fleet Quantity At Year End</u>
1979	1	1	12
1980	2	2	36
1981	3	2	60
1982	4	2	84
1983	5	2	100 (Aug. 1983)

2. Service Introduction - first airplane 1/1/79, each airplane immediately upon delivery.

3. Airplane Replacement Schedule - one 727 retired for each new airplane into service.

4. Average Flight Length - 1.25 Hours; Average Daily Flying Per Airplane - 7.88 Hours.

5. Engine Flight Hours and Total Removal Rates

<u>Year In Service</u>	<u>Engine Hours</u>	<u>Total Engine Removal Rate (Per 1000 Engine Hours)</u>	
		<u>Reasonably High Level</u>	<u>Reasonably Low Level</u>
1	56,382	1.25	1.0
2	216,312	1.25	1.0
3	423,408	1.25	1.0
4	630,504	1.05	.83
5	823,132	.87	.67
6	862,900	.70	.51
7 & Sub.	862,900	.50	.35

6. Spare Power Plant Locations - ORD, DFW, LGA, LAX, JFK, TUL.

7. Transportation - commercial truck. Air transportation or engine inoperative ferry flights not considered.

8. Shop Process Times

<u>Year In Service</u>	<u>Calendar Days</u>
1	34
2	31
3	27
4	25
5 & Sub.	24

9. Basic Engine Cost Complete - \$1,050,000 ea. (1972 Value).

10. Power Plant Installation - \$430,000 ea. (1972 Value).

TABLE IV- 6

STF-429 Power Plant Spares Support

Spare Power Plant Requirements and Investment

<u>Year In Service</u>	<u>Spare Power Plant Quantities</u>						<u>Investment (\$-Million)</u>	
	<u>Shop</u>		<u>Field</u>		<u>Total</u>		<u>Removal</u>	<u>Rate</u>
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>		
1	8	6	6	6	14	12	20.58	17.64
2	28	22	8	7	36	29	52.92	42.63
3	45	37	13	10	58	47	85.26	69.09
4	51	43	15	11	66	54	97.02	79.38
5	55	41	15	14	70	55	102.9	80.85
6	47	35	13	11	60	46	88.2	67.62
7 & Sub.	38	24	11	8	49	32	72.03	47.04

a. Complete Spare Power Plants

An American Airlines proprietary computer program was utilized to determine the total quantities of complete spare power plants in shop process, plus in transit to and from field stations plus located at field stations as ready spares. This program relates the following parameters to determine the total quantity of spare power plants, the quantity allocated to each field station and the quantity in shop process:

1. overall engine removal rate
2. frequency of flights per station
3. transportation time to and from the individual stations
4. shop processing calendar days
5. percentage of the time power plant removals can be planned at stations stocking spares.
6. specified percentage of the times each stocking station will have a spare power plant when needed.

This analysis was made for the conditions defined in Table IV-5 at both engine removal rates listed. Table IV-6 shows the results of this analysis.

Several facts should be noted in Table IV- 6 :

1. the investment impact of a higher removal rate
2. the rapid buildup of spares requirements in the first three years, the level out in the fourth and fifth, and reduced requirement in the sixth, seventh and subsequent
3. the requirement peak during the fifth year - the year in which the last airplane is delivered. This obviates the diversion of any of the 23-21 excess power plants to the late delivery airplanes unless delivery schedules are revised
4. the opportunity for management to reduce the peak investment of \$103 million through judicious exercise of the various options available.

b. Shop Support Spares

Shop support spares investment levels for the STF-429 are based upon current American Airlines practices. These practices have been updated periodically since original jet power plant provisioning (707/JT3, beginning in 1957). Accumulated experience is used to refine them - always working toward maximum coverage at minimum investment. The provisioning activity for the DC10/CF6 power plants represents the application of this experience to a new fleet (1970/1972 time period). Likewise, current spares support levels for the 727/JT8 represent the application of this experience to mature fleets. Accordingly, the model used for the STF-429 power plant is derived from a composite of actual investment levels for American's CF6 and JT8 power plants. Figure IV- 8 , illustrates the model developed for determination of shop support spares investment ratios as the new fleet enters operation.

Figure IV- 9 , shows the total investment in power plant spares as the fleet builds up and also the mature level. The investment in spare power plants corresponds to that shown for the low removal rate in Table IV-6 . The investment in shop support spares was derived by applying the STF-429 ground rules to the model illustrated in Figure IV-8 .

It should be noted that the spare power plant investment increases proportionally to the fleet buildup, and reaches a peak constituting a substantial excess when the last airplane is delivered. A combination of two options might be employed to cope with this situation. Delivery of the last few airplanes could be planned for after the peak power plant demand has passed so that some of the excess can be utilized to supply the new airplanes. Also, any remaining units could be converted to parts to be utilized as shop support spares. Other but less attractive alternates would be to find a buyer for the excess or to lease the quantity surplus to the mature fleet level from a third party.

In the case of the shop support spares, the investment increase is more gradual and does not reach a substantial excess at the time new airplane deliveries are completed. This is due to the manufacturer's participation in the early problems through warranties and campaign parts replacements and because shop work on the power plants is concentrated on specific correction of deficiencies rather than broad scale reconditioning. The continual infusion of new power plants further delays the point in time at which large scale

shop activity commences with the attendant need for large quantities of shop support spares.

The magnitude of the spares investment merits careful attention by both the manufacturers and the airlines. Power plant designs must be selected which properly balance performance, reliability and low cost maintenance. The development and flight test programs must simulate airline operation as realistically as possible in order to reveal deficiencies and these deficiencies must be corrected prior to delivery of production engines. Deficiencies which show up in airline service must be dealt with effectively and expeditiously by both parties in order to minimize the peaks characteristically occurring in the early years of operation. Airline management must evaluate all of the available options peculiar to each route structure and set of operating constraints in order to arrive at the most cost effective levels of spares investment. Finally, the maintenance program must be tailored to achieve high levels of airworthiness with minimum spares support requirements.

RATIO OF INVESTMENT IN SHOP SUPPORT SPARES TO INVESTMENT IN INSTALLED POWER PLANTS

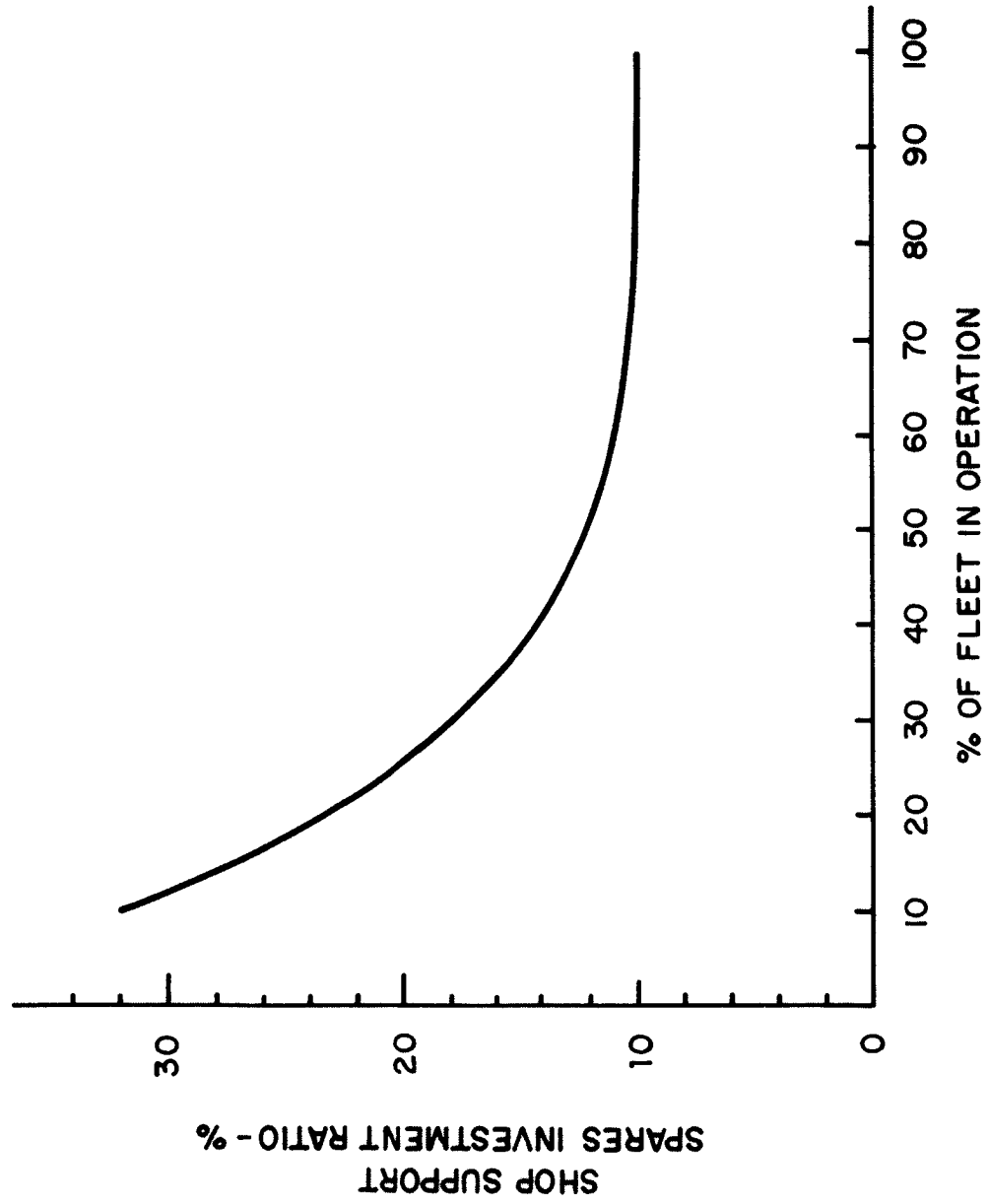


FIGURE IV -8

STF 429 SPARES INVESTMENT LEVELS VS FLEET BUILD-UP

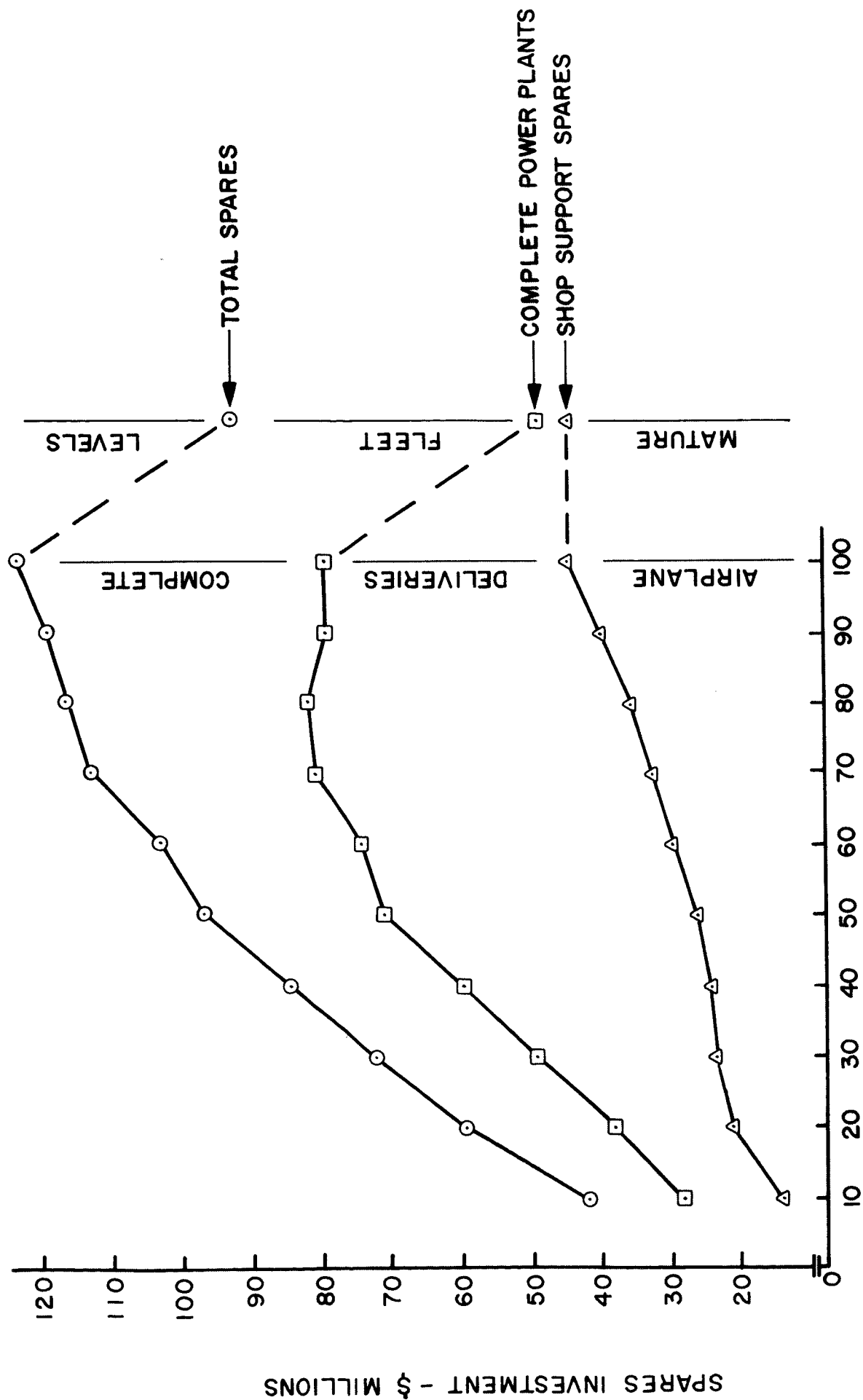


FIGURE IV-9

c. Facilities Investment

Airlines must have access to maintenance facilities at various locations across their route networks. Facilities are defined as the building-type, fixed installations which are not intended to be moved. They consist of such things as hangars, airplane maintenance work docks, shops, engine test cells, airplane parking aprons, engine run-up noise suppressors, and jet blast deflectors. Facilities investments for powerplant support differ between the line stations and the main maintenance base.

Facilities at line stations are determined principally by the total needs of the airplane. Hangars are sized to house the airplane and a relatively modest increase is required to provide for powerplant storage, changeout, and servicing. Even if a satellite shop with engine minor repair and module exchange capability is needed, its facility cost impact is insignificant. Line station hangar investment is sensitive to the following factors:

- | | |
|-------------------------|---|
| 1) Route Structure | Airplane overnight locations, climatic conditions, local acquisition costs. |
| 2) Airplane Utilization | Time available for maintenance activity. |
| 3) Fleet Size | Total system hangar floor-space requirement, hangar size at major line maintenance bases. |

- | | |
|------------------------|---|
| 4) Maintenance Program | Frequency/location of scheduled maintenance activity, division of activity between line stations and main base. |
| 5) Fleet Composition | Size/configuration compatibility of the various airplanes. |
| 6) Pooling Opportunity | Potential for leasing existing facilities from others. |

Integrating these factors into an airline's individual situation could result in line maintenance hangar investments ranging from a few minimum-capability units at \$750,000 each to several \$25,000,000 superbay hangars capable of housing four 747s plus two DC-10s.

Facilities investment at the main maintenance base of a major trunk airline can be in the 30 to 50 million dollar range. Hangar space for the total airplane must be provided and repair shops for airplane components and powerplants are also required. Here, the provisions for powerplant repair assume a larger proportion of the total investment. Provisions must be made for housing such operations as plating; welding; heat treating; assembly and disassembly of large and heavy modules; cleaning and testing using explosive, toxic, flammable liquids; foundation stabilization and isolation of large machine tools and balancing machines; and, area protection for radioactive inspections. Also, engine test cells are required with structural and airflow capacity adequate for the engines being processed and with environmental safeguards to comply with community regulations.

The magnitude of the investment is influenced not only by the size

and quantity of the powerplants in the fleet, but also by management policy regarding degree of self-sufficiency versus outside agency contracts. The latter is a tradeoff between commitment of capital and reduction of direct operating expense.

STF 429 Powerplant Facilities

Introduction of the Model D4-179C/STF 429 into a major trunk airline's fleet would have a modest facilities investment cost impact, especially assuming that existing model airplanes would be replaced on a one-for-one basis. If retirement of the older airplanes were delayed, additional facilities would be required to accommodate the increased maintenance volume.

In the case of American Airlines, hangars of adequate size are available at most line stations which would be served by the new airplanes. At the main maintenance base, hangars, shops, and test cells sized for larger powerplants than the STF 429 are currently in operation. The following facilities investments, in terms of 1972 values, are estimated for accommodating the new airplanes:

- 1) Additional "tail-in" partial hangars
located at two principal line stations
(\$800,000 ea.) \$1,600,000

- 2) Maintenance work docks at three
principal line stations and at the
main maintenance base (\$250,000 ea.) \$1,000,000

3) Additional warehouse-type facilities for new airplane and powerplant spare parts	<u>\$ 250,000</u>
TOTAL	<u>\$2,850,000</u>

The foregoing facilities investments are determined principally by the total airplane requirements and the increment attributable to powerplants is in the order of 10% to 20%. The major investment for powerplant maintenance support is in the area of tooling and equipment which is discussed in the following paragraphs.

d. Tooling/Equipment Investment

Airline operation of an airplane requires that a wide array of tooling and equipment be provided. The size and composition of the existing fleet is significant. If the airline is operating an equivalent sized fleet of similar airplanes which will be phased out as the new fleet is phased in, a minimum additional investment will be required. If the new fleet is substantially different (i.e. 707 vs 747) or if the new airplanes are added to the existing ones, a high investment level may be necessary. Of the equipment needed, part can be regarded as general purpose; that is, applicable to all of the various airplane models in the operator's fleet. Other pieces of equipment are specialized and must be acquired to support the new airplane in spite of the existence of basically similar items supporting the current fleet.

In determining the applicability of general purpose equipment to the new fleet, the operator must consider size and quantity factors. If equipment is already available which is of sufficient size and strength to accommodate the new flight items, considerable expense can be avoided and the lead time shortened in providing for this area of support. If size and strength are adequate, there may still be a problem since the existing equipment may be already utilized to full capacity or there may be insufficient unused capacity to meet the new equipment's needs. This can be a challenging aspect of resources management since a big strain is imposed upon initial support capacity during the time interval when the new airplane is being phased in. If this situation is not managed well, the early operation will suffer from lack of adequate equipment support due to peaking of unforeseen new problems. If however, support equipment

is provided on the basis of peak demand for the initial operation, there will be a large surplus when the new fleet has settled down into a routine operation.

Support tooling and equipment is usually capitalized since its useful life is longer than that of the flight equipment.

Power Plant support is required in two principal categories:

- 1) that required by processing at the main maintenance shop (and at satellite maintenance shops if such are utilized); and,
- 2) that required for transportation, storage, installation and removal.

Shop tooling/equipment can be classified as follows:

Main Engine Shop

Work stands to support the complete power plant, the bare engine, modules and large sized engine parts.

Engine/modules inter-shop transport stands parts storage racks.

Special hand and power tools.

Special hoisting and handling tools.

Parts storage racks

Flow and leak test rigs

Balancing machines and fixtures

Measuring and non-destructive test equipment

Machine and Processing Shops

General purpose machine tools and jigs/fixtures

Welding machines and jigs/fixtures

Plating equipment and fixtures

Heat treat equipment and fixtures

Special process equipment (such as: flame spray, vacuum furnaces, electrostatic discharge milling machines).

Component Shops

Thrust reverser work and test stands

Fuel control and fuel pump test benches and adapters

Fuel nozzle special assembly tools and flow and calibration stands

Valve and actuator flow and calibration stands and fixtures

Engine indicator system special tooling and calibration equipment.

Miscellaneous Support

Laboratory for calibration of measuring devices, gages, test instrumentation, scales, torque wrenches, etc.

Chemical/mechanical lab for plating solution monitoring, engine oil analyses, microscopic examination, tensile testing, photographic analysis, etc.

X-ray lab

The following equipment is required for moving the power plant to the airplane, for installation and removals, for troubleshooting and for servicing: (it should be noted that engine change capability is required at several stations throughout the route network since the time and place for changes cannot always be forecast accurately)

Transport stands and shipping covers

Special installation removal tool kits and hoisting slings

Temporary holding fixtures for power plants, modules, components, cowl panels, etc.

Power hoists

Diagnostic instruments, borescopes, x-ray and radio isotope equipment
Miscellaneous servicing tools

STF429 Power Plant Tooling/Equipment Requirements

In order to portray the impact of a new fleet of airplanes upon a typical airplane operation, the cost to American Airlines of providing tooling and equipment for the new power plant was studied. Full advantage was taken of existing equipment since it was assumed that one Boeing 727/JT8 power plant would be retired for each new STF429 power plant introduced. Costs at 1972 values are estimated as follows:

<u>Tooling/Equipment Items</u>	<u>Remarks</u>	<u>Cost</u>
<u>Main Maintenance Shop</u>		
Engine Shop (including quality assurance instrumentation)	Assumes maximum use and adaptation of existing support equipment.	\$1,000,000
Machine & processing shops	Same	300,000
Test Cell	Adaptation of test cell already having adequate thrust capacity	325,000
Component Shops	General shop adaptation	275,000
Fuel control electronic supervisory unit	Not utilized on current power plants	50,000
General Shop Rearrange- ment	Principally a labor cost	<u>100,000</u>
	Sub Total Main Shop	\$2,050,000

Transportation & Installation/Removal

<u>Tooling/Equipment Items</u>	<u>Remarks</u>	<u>Cost</u>
Engine change tool kits (including slings)	Kits located at seven main line stations	\$ 56,000
Engine shipping stands and covers	One stand for each spare power plant (39) plus 9 spares used for engine transfer and handling during engine change	396,000
	Sub Total Shipping & Handling	<hr/> \$ 452,000
	GRAND TOTAL	\$2,502,000

This tooling/equipment cost, while substantial since it must support power plants for a 100 airplane fleet, should be considered relatively modest. Expensive machine tools, balancing machines, fuel control test stands, test cells, etc. are already available for a fleet of comparable size. These costs represent a maximum of adaptation and a minimum of new purchases.

e. Depreciation of the Investment in Equipment, Spares and Support

The depreciation schedule selected for this study is 14 years to 10 percent residual. While actual depreciation schedules vary between airlines and also for different equipment types, the selected schedule is representative of recent industry average depreciation schedules reported on wide-body aircraft purchases.

The investment costs to be depreciated in direct operating costs are the aircraft purchase price (including installed engines) and spares. The investment in propulsion system tooling and maintenance facilities is normally depreciated in indirect operating costs accounts under "ground equipment and facility" and is spread across the entire airline operating fleet of aircraft.

For the purpose of this study, the tooling and facility cost will be carried in the indirect cost area and will be depreciated against this specific fleet of airplanes. The only reason for presenting this information is that future engines may require very specialized tooling and facilities which should not be neglected in considering the economic impact or cost/benefit of a specific propulsion system approach. For this particular engine/airplane, no special circumstances of this kind exist, however, engines greater than 50,000 lbs. of thrust, larger than 8 feet in diameter or with airflows larger than approximately 2,000 pounds per second would require substantial investments in new test facilities. In the case of engines larger than 8 feet in diameter, special transportation stands and provisions to disassemble the engine to permit transportation by truck (split fan case) are

required.

The depreciation element of direct operating cost per aircraft operating hour is as follows:

Aircraft & Engine Price	\$14,750,000
Less 10%	<u>1,475,000</u>
Expense to be Depreciated	\$13,275,000

$$\begin{aligned}
 \text{Utilization (Block Hrs.)} &= \left[1 + \frac{\frac{4275}{1}}{\text{BT} + .3} + 475 \right] (P) \\
 &= \left[1 + \frac{\frac{4275}{1}}{1.8} + 475 \right] (14) \\
 &= \left[\frac{4275}{1.5555} + 475 \right] = 3225 (14) = 45150 \text{ Hours}
 \end{aligned}$$

P = Number of Years (14) FT = Flight Time (1.25)

BT = Block Time (1.5)

Depreciation = 294.00/Block Hr.

Depreciation Flight/Hour = 292.50 X $\frac{\text{B.T.}}{\text{F.T.}}$ = \$353/Hr.

Engine Depreciation \$/Ft. Hr. = $\frac{(.90) (3,150,000)}{45150} \frac{1.5}{1.25} = 75.30$

Power Plant = $\frac{(.90) (3,150,000 + 1,290,000)}{45150 \times 1.25} = \106.20
\$/Ft. Hr.

	\$/Ft. Hour	\$/Block Hour
Total Aircraft	\$353.00	\$294.00
Engine (all)	25.10 (75.30)	20.90 (62.70)
Power Plant (all)	35.40 (106.20)	29.50 (88.50)

The depreciation of the investment in aircraft and engine spares has in the past been based on 6% of aircraft purchase price as airframe spares and 30% of the installed engine prices as engine spares. However, as previously discussed, a significant portion of airframe spares are in fact spare engine build-up kits and other propulsion system items bought from the airframe contractor. The total value of spares has been held but the spares directly for supporting the propulsion system have been identified. From section IV.C.2.b. the spare engines, parts modules, and engine buildup kits (QEC') are estimated to reach 39.2% of the engine investment during the introduction into service. The mature spares ratio does in fact drop to 29.4% or 30% price equivalent as the engine matures. The initial investment therefore reaches 123.6 million dollars for the fleet of 100 aircraft or \$1,236,000 per aircraft. As the engine matures, the excess engines may be broken into spare parts or installed on new aircraft. The decision to put into spares, install on new aircraft or perhaps sell would vary from airline to airline. For the purpose of the study, the initial power plant investment has been written down to 10% over 14 years or 4,515,000 operating hours. Based on ATA, the total spares value of 1,641,000 dollars per aircraft remains the same at \$32.71 per flight hour of which \$24.64 per flight hour is propulsion spares.

The depreciation of the investment in power plant facilities, \$2,850,000, and tooling of \$2,502,000 would be written off over the full aircraft fleet.

$$\frac{\$}{\text{Hours}} = \frac{\$ 5,352,000}{4,515,000} = \$1.18/\text{Block Hour}$$

or \$1.42 per Flight Hour

This cost would be carried in the indirect operating expense area.

3. Fuel Costs

Fuel is a major operating expense item the magnitude of which is determined by the size of the airplane (primarily the number of seats), the engine specific fuel consumption, and the price of fuel. In the recent past the variation in fuel price has far outshadowed the other effects. Figure IV-10 shows the direct operating cost of the base line airplane broken down by major cost element and with fuel price as a variable.

At 11 cents a gallon the fuel expense represents about 15% of the direct operating cost. At this relative value in relationship with the crew cost and depreciation expense (a function of utilization) the most economical cruise speed (least cost cruise) was near a high speed cruise schedule. At 28 cents a gallon the fuel expense becomes approximately 32% of the direct operating cost and becomes the dominant operating expense element and makes the least cost cruise condition nearly identical to the long range cruise. At the average flight distance for this aircraft, fuel represents a cost of \$324.45 per hour based on 18¢/gallon.

There are a number of areas where changes in operational procedure can reduce fuel consumption. The overall economic suitability of procedural changes must be assessed for a particular airplane in the context of particular operational environments. The impacts of some of these alternatives are shown below:

Cruise Speed Reduction

From minimum cost cruise 0 to 4%

From high speed cruise 2 to 12%

Optimum cruise altitude 0 to 4% within 4000 ft. of optimum

2 to 12% from 4000 ft. to 8000 ft. below optimum

Instrument calibration	1 to 2% per .01 Mach slow indication
Engine TSFC recovery	0 to 6%

4. Propulsion System Maintenance Cost

The following section presents the analysis of the estimated maintenance cost of first the mature engine; and second the estimated cost during the introduction into service.

a. Estimated Mature Propulsion System Costs

The estimated propulsion system costs are addressed as the costs to maintain the power plant on the flight line and the costs to maintain the basic engine and installation in the shop.

DIRECT OPERATING COSTS MODEL D4-179C

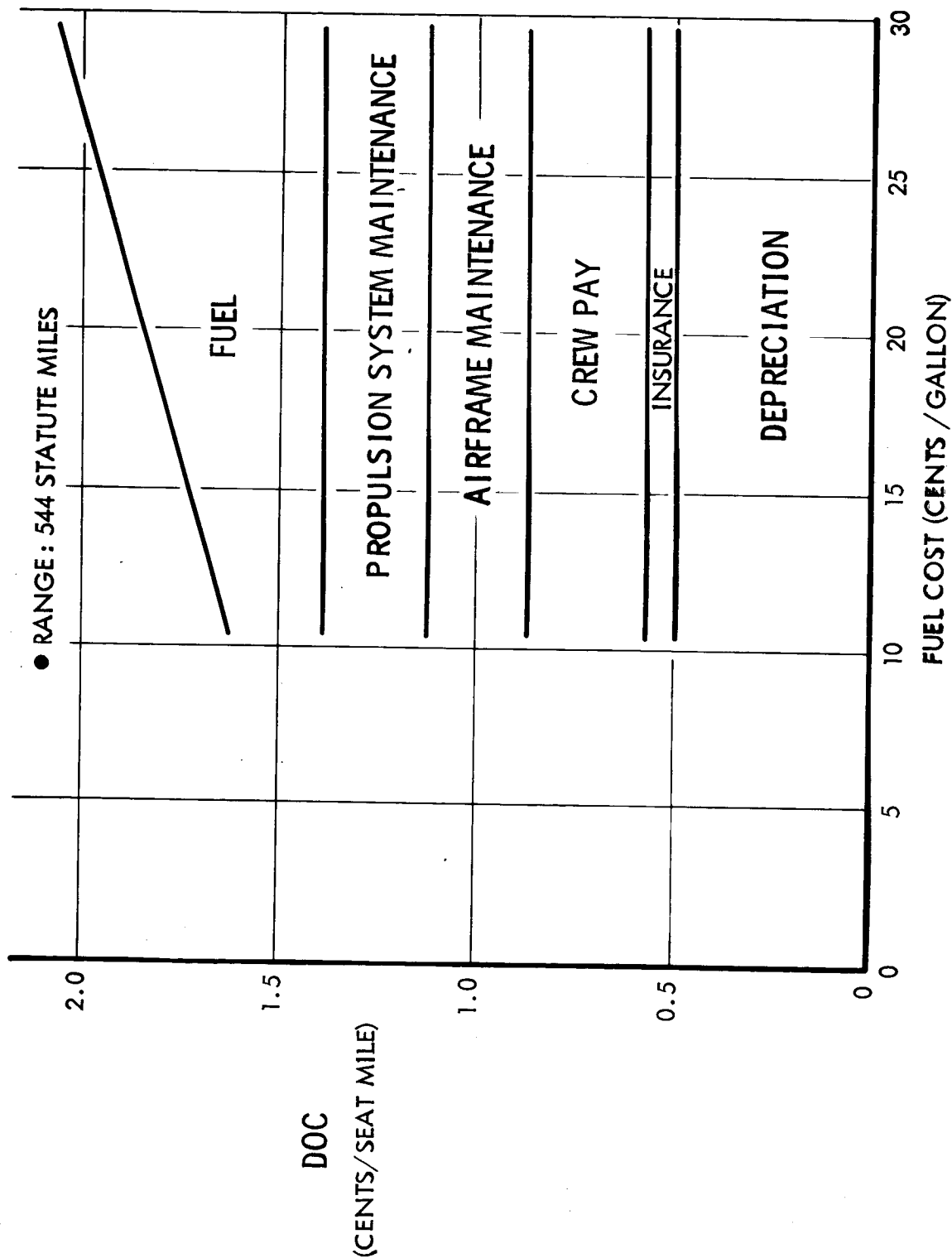


FIGURE IV-10 EFFECT OF FUEL PRICE ON AIRPLANE
DIRECT OPERATING COST

1. Power Plant Installation - Build Up of Costs.

General

The power plant installation includes all components installed on the basic engine by the airframe manufacturer and identified in the ATA systems 71 through 80. These components include the inlet, side cowl, thrust reversers, engine instrumentation and transducers supplied by the airframe manufacturer, starting system service bleed system and control systems. The installation maintenance cost data excludes premature replacement and all maintenance repair costs on the constant speed drive, AC generator and the hydraulic pumps which are run off the engine gear box, because these costs are accumulated in the appropriate airframe ATA systems and not in propulsion. Only the maintenance costs incurred to remove or install these components during power plant QEC tear-down or build-up are included.

Quick Engine Change (QEC)

727 historical data indicates an average of 25 manhours are required to replace a fuselage mounted QEC. It is predicted that the fuselage mounted QEC replacement on the study airplane will require an average of 27 manhours. (Figure IV- 11) The timeline illustrated in Figure IV-12 represents ideal conditions.

The build-up and tear-down of the basic engine to or from a QEC for the 727 fuselage mounted configuration is 100 manhours and 20 manhours respectively. It is predicted that these values for the study aircraft will be 140 and 30 manhours based on a regression analysis of historical data which developed the curves on Figure IV- 11.

Predicted Total Line and Installation Shop Direct Maintenance Costs

Assuming the basic engine labor and material costs will be determined using a predicted engine removal rate (ERR) corrected for flight length, the total line direct labor and material and installation shop direct labor and material costs can be predicted for study aircraft at 1.25 average flight length as follows:

- Total Line Direct Labor (LL_T) - Manhours per Engine Flight Hour
 - a) 2 (Installation Line Labor) = Total Line Labor (Inst'l + Basic Engine)

$$2 \left[LL_{71} + \frac{X}{1.15} (LL_{78} + LL_{80}) + LL_R \right] = LL_T$$

X = Ratio of labor cost at study flight length, Figure IV- 13

Subscript numbers represent particular ATA systems and

"R" represents the remaining power plant ATA's excluding 72.
 - b) $LL_{71} = ERR \times 1.30 \times (MH)$

ERR = Engine Removal Rate per 1000 Engine Flight Hours =
0.50/1000 EH

MH = Manhours for Engine Replacement = 27

1.30 = Factor to Account for Cowl and Some QEC Repair

$LL_{71} = 0.50/1000 \times 1.30 \times 27 = 0.018 \text{ MH/EH}$
 - c) $LL_{78} = N \times 0.020$

N = Number of Thrust Reversers per Engine = 2

$LL_{78} = 2 \times 0.020 = 0.040 \text{ MH/EH}$
 - d) $LL_{80} = 0.006 \text{ MH/EH}$
 - e) $LL_R = ERR \times 75$

$LL_R = 0.50/1000 \times 75 = 0.037 \text{ MH/EH}$
 - f) $LL_T = 2 \left[0.018 + \frac{1.15}{1.15} (0.040 + 0.006) + 0.037 \right] = 0.202 \text{ MH/EH}$

$= 0.202 \times 7.00 = \$1.41/\text{EH}$ or $\$4.23/\text{FH}$
- Total Line Material (LM_T) - 1972 Dollars per Engine Flight Hour
 - a) $LM_T = 0.00133 \times \text{Engine Price} \times ERR$

$ERR = 0.50/1000 \text{ EH}$

Engine Price = \$1,050,000

$LM_T = \frac{0.00133 \times 1,050,000 \times 0.50}{1000} = \$0.70/\text{EH}$ or $\$2.10/\text{FH}$
- Installation Shop Direct Labor (SL Instl) - Manhours per Engine Flight Hour
 - a) $SL_{71} + \frac{X}{1.15} (SL_{78} + SL_{80}) + SL_R = SL \text{ Instl}$
 - b) $SL_{71} = ERR \times 1.30 \times (MH)$

ERR = Engine Removal Rate Per 1000 Engine Flight Hours = 0.50/1000/EH

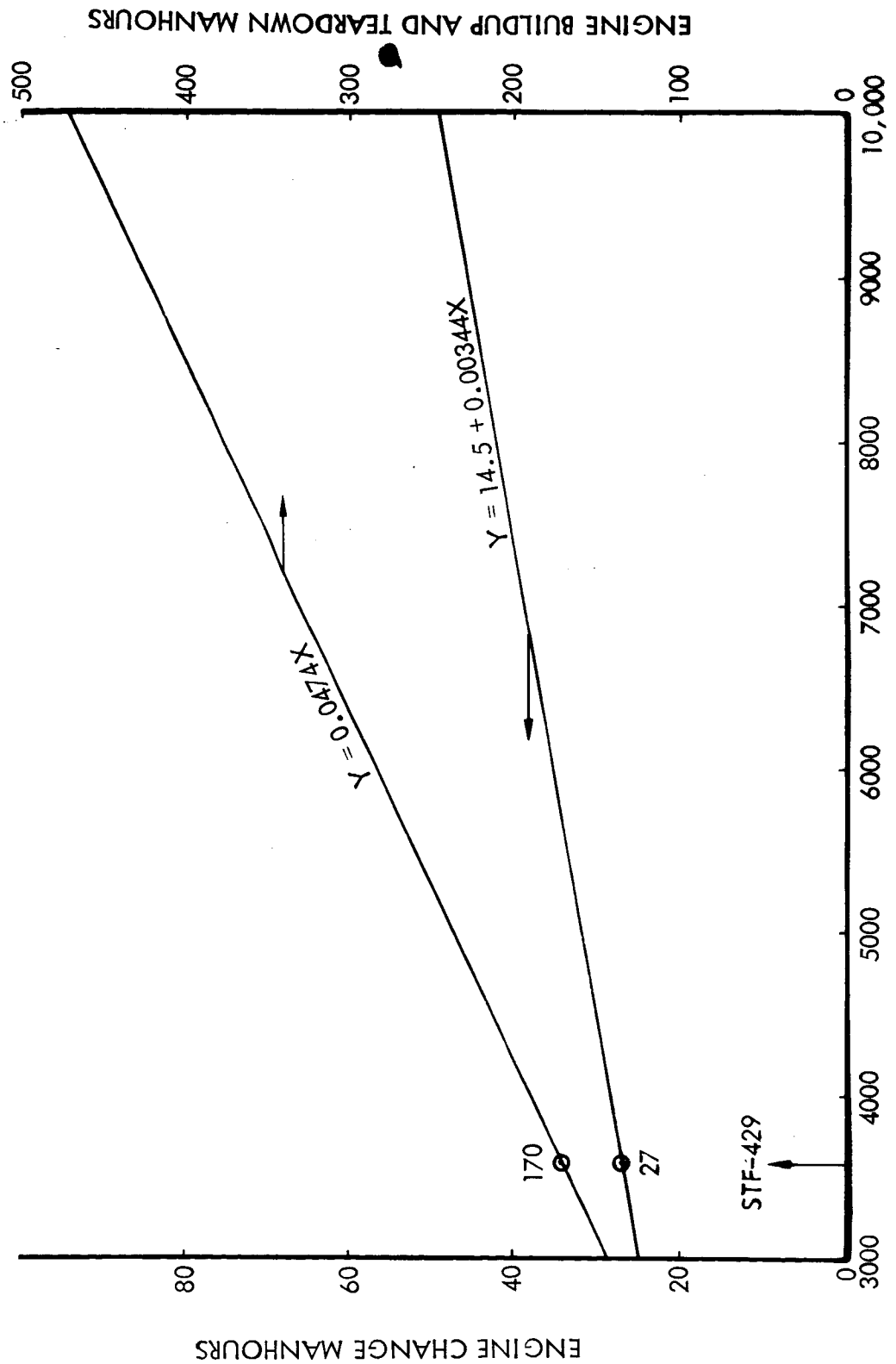
MH = Manhours for QEC Build-up and Tear-down = 140 + 30 = 170

1.30 = Factor to Account for Cowl and Some QEC Repair

$SL_{71} = 0.50/1000 \times 1.30 \times 170 = 0.110 \text{ MH/EH}$

- c) $SL_{78} = N \times 0.04$
 $N = \text{Number of Thrust Reversers per Engine} = 2$
 $SL_{78} = 2 \times 0.04 = 0.08 \text{ MH/EH}$
- d) $SL_{80} = 0.014 \text{ MH/EH}$
- e) $SL_R = \text{ERR} \times 75$
 $SL_R = 0.50/1000 \times 75 = 0.038 \text{ MH/EH}$
- f) $SL \text{ Inst} = 0.110 + \frac{1.15}{1.15} (0.080 + 0.014) + 0.038 = 0.242 \text{ MH/EH}$
 $= 0.242 \times 7.00 = \$1.69/\text{EH} \text{ or } \$5.07/\text{FH}$
- e. **Installation Shop Material (SM Instl) - 1972 Dollars per Engine .**
Flight Hour
- a) $SM_{71} + \frac{Y}{1.19} (SM_{78} + SM_{80}) + SM_R = SM \text{ Instl}$
 $Y = \text{Ratio of Material Costs at Study Flight Length, Fig. IV-14}$
- b) $SM_{71} = 0.0015 \times \text{Engine Price} \times \text{ERR}$
 $SM_{71} = \frac{0.0015 \times 1,050,000 \times 0.50}{1000} = \$0.79/\text{EH}$
- c) $SM_{78} = N \times \$0.30$
 $N = \text{Number of Thrust Reversers per Engine} = 2$
 $SM_{78} = 2 \times 0.30 = \$0.60/\text{EH}$
- d) $SM_{80} = \$0.15/\text{EH}$
- e) $SM_R = 0.0007 \times \text{Engine Price} \times \text{ERR}$
 $SM_R = \frac{0.0007 \times 1,050,000 \times 0.50}{1000} = \$0.37/\text{EH}$
- f) $SM_{\text{Instl}} = 0.79 + \frac{1.19}{1.19} (0.60 + 0.15) + 0.37 = \$1.91/\text{EH} \text{ or } \$5.73/\text{FH}$

PREDICTED ENGINE CHANGE AND BUILDUP AND TEARDOWN MANHOURS



ENGINE WEIGHT (POUNDS)

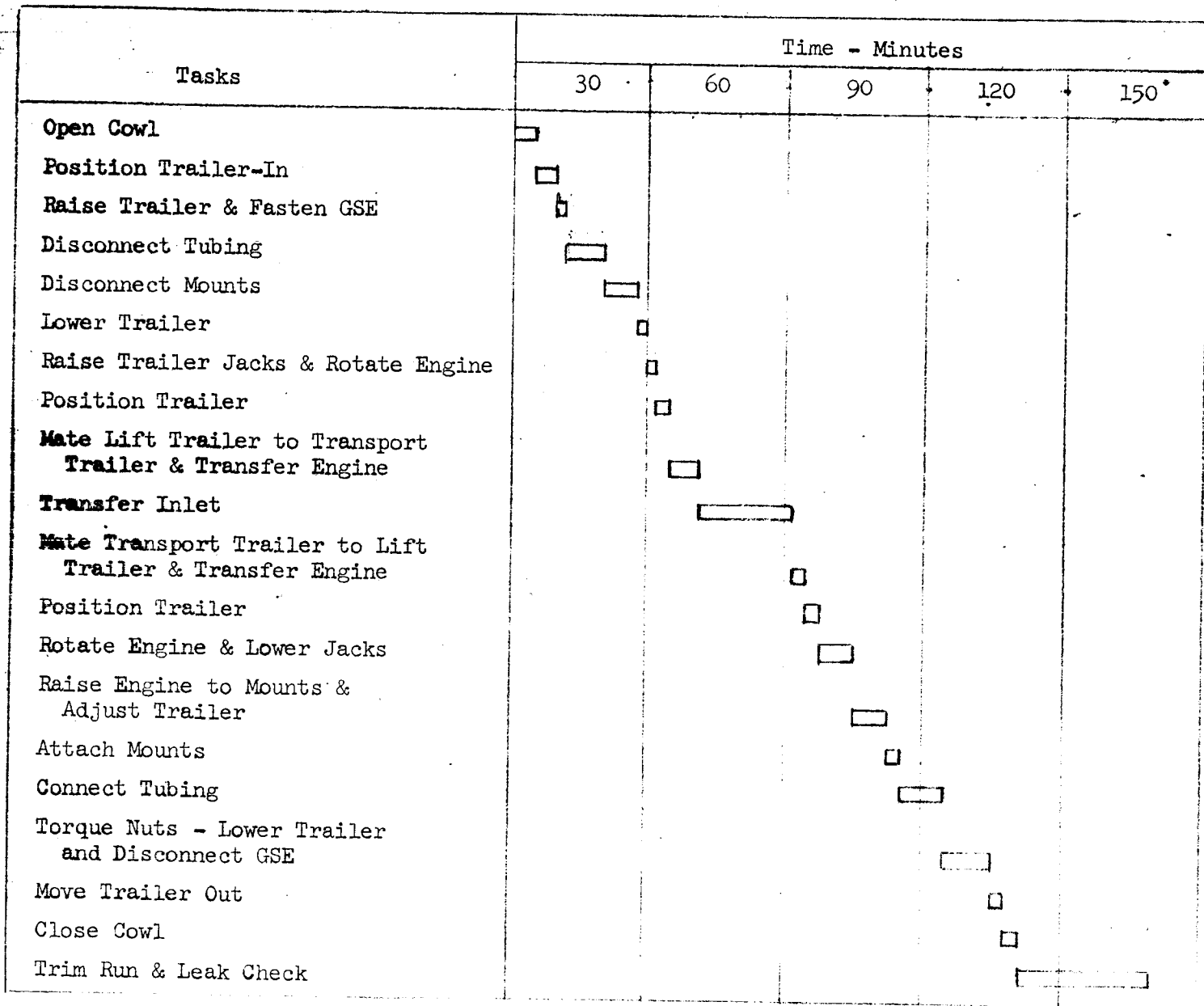
FIGURE IV-11 PREDICTED ENGINE CHANGE AND BUILDUP AND TEARDOWN MANHOURS

FIGURE IV-12
ENGINE CHANGE TIME ANALYSIS

FUSELAGE-MOUNTED POD

MODEL: D4-179C

ENGINE: STF 429 MOD.



Note: 5 men are required.

ENGINE - LABOR

ALL MODELS

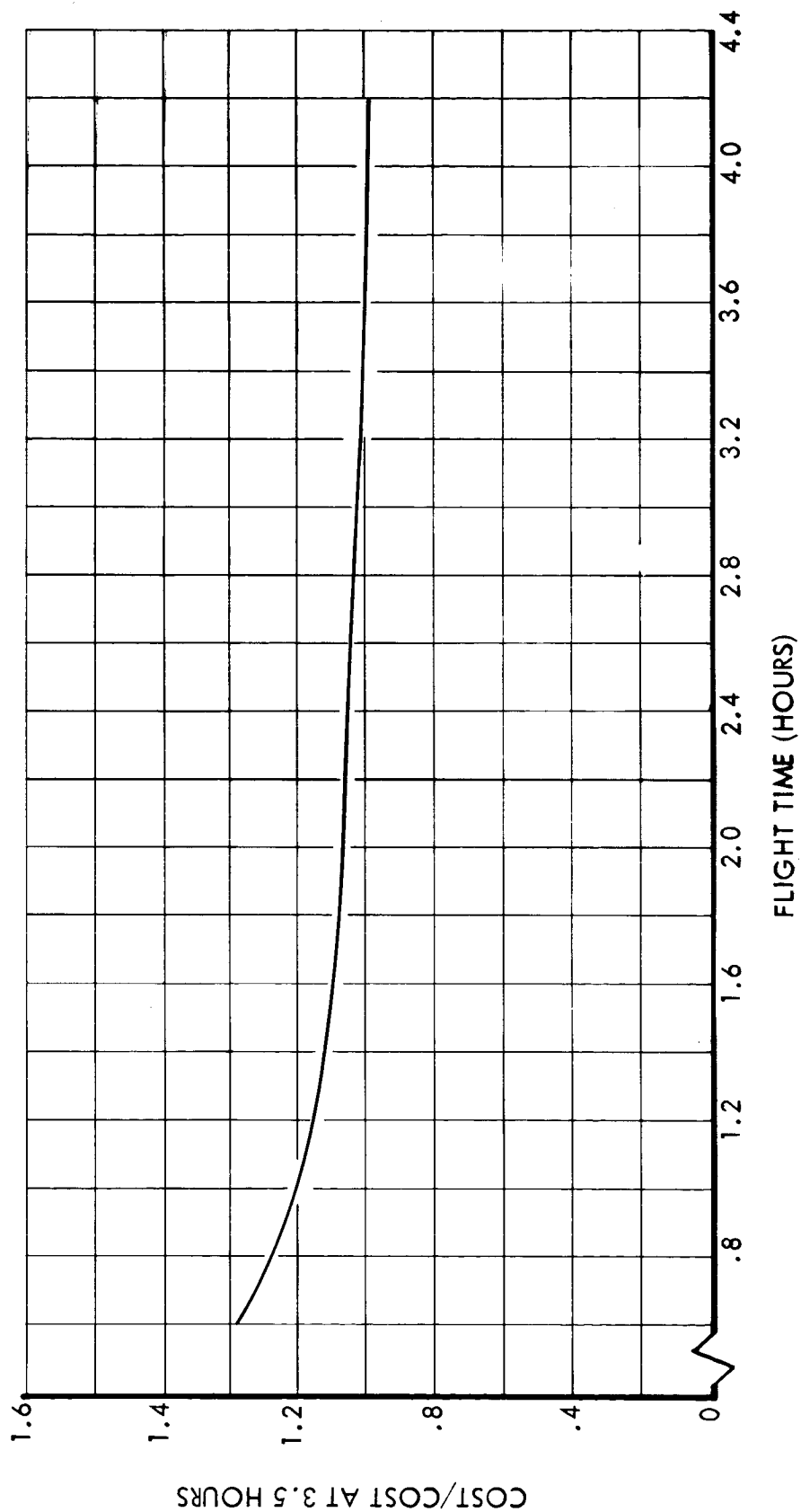


FIGURE IV-13 ENGINE LABOR

ENGINE - MATERIAL

ALL MODELS

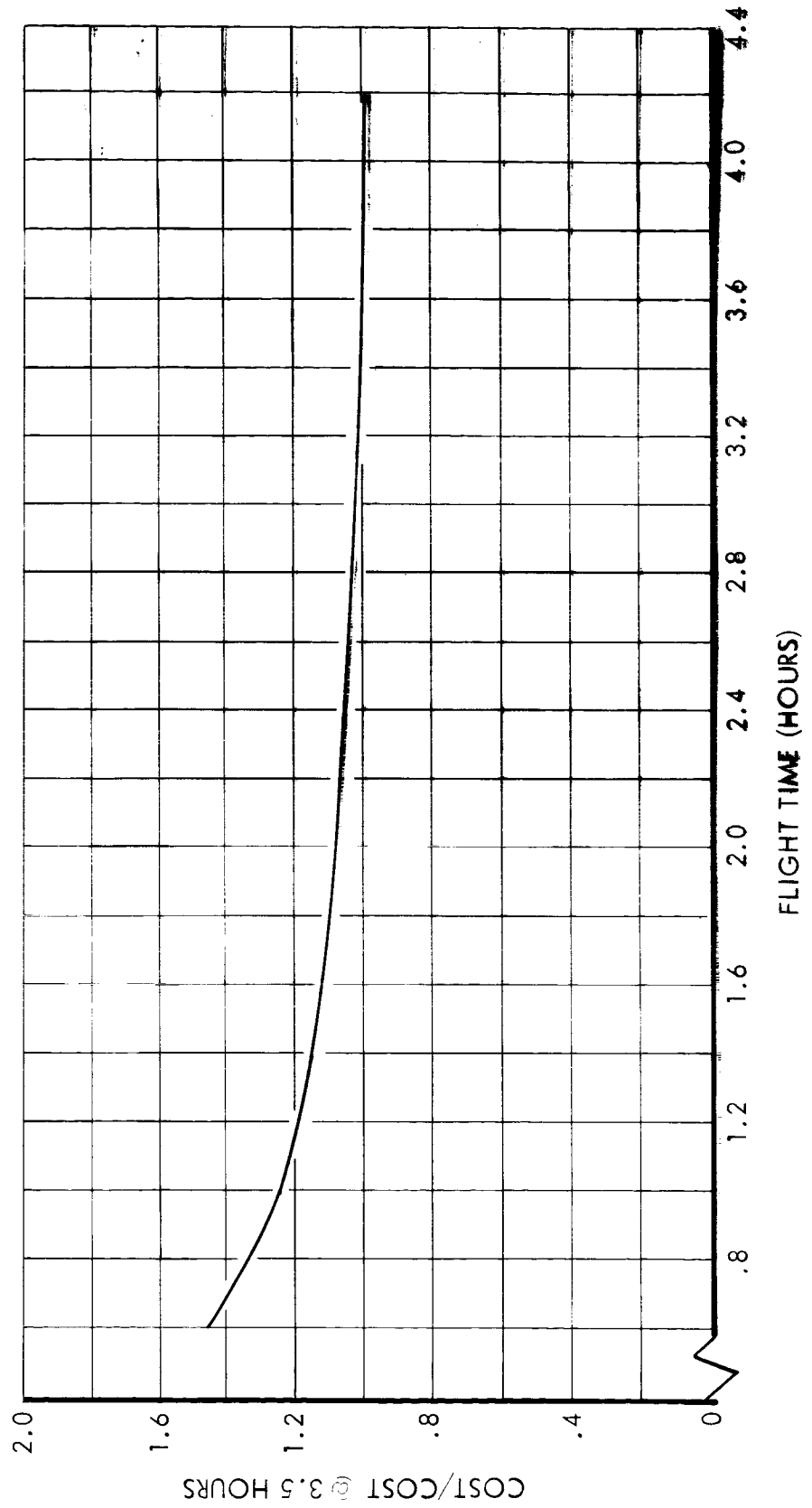


FIGURE IV-14

To summarize, the line maintenance labor on both basic engine and installation is estimated to be 0.202 manhours per engine flight hour. At a direct labor rate of \$7.00 per hour, this is equal to \$1.41 per engine flight hour. Line maintenance material costs are estimated at \$.70/engine flight hour. Line maintenance costs are then \$2.11 per engine flight hour on a direct labor base and \$5.04 per engine flight hour on a fully allocated labor basis.

Shop maintenance on the installation items is \$1.69 for direct labor (\$5.20 fully allocated labor) per engine flight hour and material is \$1.91 per engine flight hour. The cost for basic engine shop maintenance is estimated in the following paragraphs.

2. Basic Engine - Buildup of Costs

This section presents the shop maintenance cost for the mature STF 429 basic engine. With a 1.25 hour flight length. The preceding section covers shop costs of the power-plant installation plus all line maintenance for the installation and basic engine.

The STF 429 engine maintenance cost is estimated to be \$56.61* per engine flight hour (EFH). This estimate was calculated using the trends and techniques established in Section III. Values for the STF 429 modular sections were read off the curves for Manhours Per Repair, Mean Time Between Repair, and Maintenance Material Cost per Repair/Price, the key elements required in calculating maintenance cost. Figure IV-15 shows the values of various STF 429 engine parameters needed for predicting its maintenance cost.

The STF429 maintenance cost predictions assume that the trends established by the JT3D, JT8D and JT9D are applicable to this advanced engine. The current engine trends include the effects of many significant maintenance cost related design advances that resulted from the experience gained between the time of introduction of the JT3D and the design of the JT9D. However, these trends cannot reflect any acceleration of the rate of improvement that may result from increased emphasis on maintenance cost technology. Therefore, the current engine trends and the STF429 predictions should serve as challenges to the industry to find ways of beating these trends. The STF429 maintenance cost build-up and the sensitivity analysis performed can also be used to help establish the priority order of technology advances.

The following paragraphs will elaborate on the components that comprise the maintenance cost prediction for the STF 429 basic engine.

* Based on Fully Allocated Labor Rate.

a. Maintenance Labor Cost

1. Module Manhours Per Repair

The estimated average labor manhours per repair for each of the major modules of the STF 429 are summarized in Figure IV-16. The JT3D, JT8D and JT9D labor manhours per repair data from Section III is also included for comparison. The Section III correlation plots were duplicated for this section and marked to show the STF 429 inputs and outputs. These plots are referenced as each module is discussed in the following sections.

Compressor Manhours Per Repair (Figure IV-17)

Unlike the engines on which the correlation is based, the STF 429 has only a two stage fan and no compressor stages on its low-speed rotor. This low number of stages results in a low predicted value (190) for its manhours per repair. Inherent in this estimate is the assumption that the STF 429 fan blades, which are fabricated from an advanced composite material, have similar resistance to impact damage and ease of repair characteristics to the titanium blades used in the other engines. The significance of this assumption to the total maintenance cost of the STF 429 is explored parametrically in paragraph C.4.a.2.d.

The high tip speed of the STF 429 high compressor is primarily responsible for its relatively high predicted value of 445 manhours per repair, since its diameter is similar to the JT3D and JT8D high compressors and its number of stages is one less than the JT9D. It has been assumed in this analysis that the STF 429 compressor, which has drum rotor construction with cantilevered stators and a split compressor case, has similar repair requirements to the JT3D, JT8D and JT9D engines. There are some indications that the STF 429 features will tend to reduce the manhours per repair. The impact of different manhours per repair for the high compressor will be discussed in paragraph C.4.a.2.d.

Diffuser Manhours Per Repair (Figure IV-18)

Based on the qualitative analysis performed, the STF 429 diffuser module is predicted to require 150 manhours per repair which is lower than the best of the other engines. The STF 429 diffuser case supports only one bearing and is of a non-welded construction in that the inner and outer walls of the case, the bearing support and compressor exit vanes are bolted together as an assembly. The compressor exit vanes carry the loads between the inner and outer walls eliminating the need for structural struts. One non-structural strut is provided for bearing service lines and is removable from the outside of the engine. This makes it less complex than the diffuser cases of the other engines, tending to reduce the labor required to repair it.

Combustor Manhours Per Repair (Figure IV-19)

The STF 429 combustor, based on the qualitative analysis performed, is predicted to require 258 manhours per repair, the same as the JT9D combustor. The STF 429 combustor is an annular configuration with FinwallTM construction and a complex pre-mix head design. It will operate at higher temperatures than the JT9D which tends to increase its manhour per repair value. The surface area of the STF 429 combustor, however, is considerably lower than the JT9D and this serves to reduce the manhours per repair required. The complex pre-mix head design and Finwall construction will probably be harder to repair, but its better fuel atomization characteristics should reduce the severity of hot spots and streaking on the combustor liner walls.

Turbine Manhours Per Repair (Figure IV-20)

Reading the STF 429 high turbine parameter point yields a predicted manhour per repair value of 205 which is lower than the JT9D. The STF 429 high turbine, while operating at a higher temperature than the JT9D, has the same number of stages and is smaller in diameter. Its predicted manhours per repair is about twice the JT3D due to the extra stage and high turbine temperature.

The STF 429 low turbine is about the same diameter as the JT3D and JT8D, but it operates at a slightly higher temperature and has one extra stage, resulting in its manhours per repair of 325 being slightly higher than the other engines.

2. Module Mean Time Between Repair

The estimated mean time between repair (MTBR) for each module of the STF 429, plus Section III data on the JT3D, JT8D and JT9D, are summarized in Figure IV-21 and are discussed individually below.

Compressor Mean Time Between Repair (Figure IV-22)

Despite the fact that the STF 429 does not have any low compressor stages, its two stage fan correlation characteristics are very close to the six stage fan/low compressor of the JT8D. It has slightly higher tip speed and pressure ratio per stage but a lower exit temperature than the JT8D, resulting in a MTBR value of 6300 hours. This is slightly higher (better) than that of the JT8D.

The STF 429 high pressure compressor has the highest pressure ratio per stage, highest compressor exit temperature and highest tip speed of the four engines, resulting in the lowest MTBR value of 3500 hours. The effect of the drum rotor/cantilevered stator construction on the MTBR value was not considered in this analysis. It will be explored parametrically in paragraph C.4.a.2.d.

Diffuser Mean Time Between Repair (Qualitative)

Due to the similarity in temperatures and simplicity in construction, the STF 429 diffuser was estimated to have the same MTBR as that of the JT9D which is 5925 hours.

Combustor Mean Time Between Repair (Figure IV-23)

The STF 429 combustor has the highest temperature rise of the four engines, resulting in the lowest predicted MTBR value (2400 hours). This module has the lowest MTBR of all the STF 429 modules which were analyzed, making it the controlling module for total engine MTBR.

Turbine Mean Time Between Repair (Figure IV-24)

The STF 429 high turbine has two stages as does the JT9D, but it has a higher turbine inlet temperature and tip speed thus resulting in a lower MTBR of 2680 hours compared to 2844 hours for the JT9D.

Both the STF 429 and JT9D low turbines have 4 stages, but the STF 429 low turbine has the highest expansion ratio and highest inlet temperature, resulting in a MTBR of 2800 hours which is lower than the value for the JT9D low turbine.

3. Manhour per Engine Flight Hour Calculations (Figure IV-25),

The total manhour per engine flight hour (MH/EFH) value for the STF 429 engine is calculated in two parts. The major part is represented by the six modules that were discussed earlier in this text.

The MH/EFH values for each of these modules was obtained by dividing the man-hour per repair value by the MTBR value. The resulting MH/EFH values are shown on Figure IV-25.

The second part of the total MH/EFH value comprises the miscellaneous engine sections that were not analyzed in detail. These miscellaneous sections include the intermediate/fan case, exhaust case, gearbox, engine accessories plus the miscellaneous basic engine tasks which include removal and installation of modules, test, etc. A cursory analysis of these parts indicated that

assuming the same MH/EFH value as the JT9D engine would be a reasonable assumption. It was felt that any increase in the frequency of maintenance due to higher temperatures would be offset by a reduction in the manhours per repair due to the smaller size relative to the JT9D. The predicted MH/EFH for these sections was thus estimated to be .188.

The total shop MH/EFH value for the STF 429 is the sum of the MH/EFH for the six major modules (.483) and the miscellaneous parts (.188) yielding a total value of .671 MH/EFH for a mature engine operating at a 1.25 hour flight cycle.

4. Maintenance Labor Cost (\$/EFH)

With the MH/EFH calculated, the maintenance labor cost in \$/EFH can now be computed by multiplying the MH/EFH value by the appropriate labor rate (\$/MH).

Using a labor rate of \$21.47 per manhour (which represents American Airlines fully allocated maintenance labor rate in 1972 \$), the mature STF 429 shop labor cost would be \$14.40 per engine flight hour (Figure IV-25).

b. Maintenance Material Cost

1. Module Material Cost Per Repair/Price

The estimated Maintenance Material Cost (MMC) per Repair/Price parameters for each of the major modules of the STF 429 are summarized in Figure IV-26. The STF 429 module estimates are generally based on the observations in Section III that the module MMC Per Repair/Price parameter may be considered reasonably consistent from engine to engine. Based on JT3D, JT8D and JT9D module data studied in Task I, typical mature engine MMC per Repair/Price values have been selected for each module as shown in Figure IV-26. Where the STF 429 module design configuration was considered generally similar to the base current engines, the same typical module parameter values were assumed to hold. This was assumed for the diffuser, combustor and turbine modules. More significant differences exist between the design features of the STF 429 fan and HPC modules compared

to the current engines. This results in some uncertainty regarding the ultimate mature value of the fan and HPC estimates, as discussed in the following paragraphs.

Fan MMC Per Repair/Price

The STF 429 engine design incorporates advanced composite material in its fan blades, resulting in a substantial saving in engine weight. However, the repairability characteristics of the advanced material and its ability to resist foreign object damage has not been established. The MMC Per Repair/Price of the STF 429 fan has been assumed to be consistent with that of the titanium fans of the other engines. The significance of this assumption to the total maintenance cost of the STF 429 is explored parametrically in paragraph C.4.a.2.d.

HP Compressor MMC Per Repair/Price

The STF 429 high pressure compressor utilizes cantilevered stators while the other engines use shrouded stators. Cantilevered stators are incorporated for possible performance and cost advantages but they are expected to be more susceptible to a "chain reaction" type of failure leading to progressively greater damage as the resultant debris progresses downstream. The simply supported stators in the other engines have demonstrated their ability to limit damage to the immediate area of the initial failure. The probability of a blade or stator failure in either design is similar, so the HPC MTBR would be expected to be the same for each design. However, the extent of secondary airfoil damage is estimated to be approximately 50% greater in the cantilever design. This has been interpreted as a 25% increase in MMC Per Repair/Price for the high compressor module because the airfoils represent approximately 50% of the compressor maintenance material cost.

2. Maintenance Material Cost per Engine Flight Hour Calculation

Maintenance material cost per engine flight hour (MMC/EFH) of the complete STF 429 engine is computed in two parts. The major part is obtained by combining the MMC per Repair/Price (Figure IV-26), MTBR for a 1.25 hour flight length (Figure IV-21), and the Prime High Cost Parts Price (Figure IV-15 of the six major modules in accordance with the first term of the expression:

$$\left(\frac{\text{MMC}}{\text{EFH}}\right) = \sum \left[\left(\frac{\text{MMC/Repair}}{\text{Price}}\right) \times \frac{1}{\text{MTBR}} \times \text{Price} \right]_{\text{module}} + \frac{\text{MMC}}{\text{EFH}} \text{ Miscellaneous}$$

The second part of the calculation accounts for all of the miscellaneous sections of the engine which were not analyzed in detail. As discussed in Section III, the MMC/EFH of the miscellaneous sections is approximately 11% of the total MMC/EFH. Adding this increment to the total of the six STF 429 modules results in a total MMC of \$38.75/EFH for the 1.25 hour flight cycle as shown in Figure IV-27.

c. Total Basic Engine Maintenance Cost and Mean Time Between Engine Removal-Mature Engine

The total maintenance cost comprises the labor and material costs previously described plus outside service (OSS) costs. OSS costs were found in Section III to average about 6% of the total maintenance cost (Figure III-2). This average has been assumed for the STF 429 in arriving at a total maintenance cost of \$56.61/EFH (Figure IV-28).

The mean time between engine removal (MTBER) is required for line maintenance and flight interruption estimates. This was estimated based on the observation in Section III that the ratio of MTBER to mean time between repair (MTBR) for the module most frequently repaired averages approximately 83%. The STF 429 combustor module has the lowest MTBR (Figure IV-21) of 2400 hours. Taking 83% of this value yields an estimated engine MTBER of approximately 2000 hours.

d. STF 429 Maintenance Cost Sensitivity

A sensitivity analysis has been made to evaluate the significance of the questionable assumptions that were made in predicting the maintenance cost of the STF 429 described above. The results of the analysis are presented on Figure IV-29. The STF 429 assumptions involved the fan and HPC, which are so different from the equivalent components of the JT3D, JT8D and JT9D that the predictions might be misleading.

The STF 429 fan blades are fabricated from an advanced composite material, while the other engines use titanium. It was assumed that the composite fan blades would have consistent repairability, mean time between repair, and replacement rate characteristics with titanium blades. If these assumptions are incorrect, the STF 429 maintenance costs will be affected as indicated by the sensitivity factors. The repairability assumption, which affects the manhours per repair, is very insensitive (i.e. has a very small impact on the total maintenance cost) and should cause no further concern. The mean time between repair assumption and the replacement rate assumption, which affects the maintenance material cost per repair, are moderately sensitive and probably warrant further consideration in composite material technology efforts. Composite blades must be designed and fabricated so foreign object ingestion will not cause more extensive damage than it does in titanium blades. Also, minor damage such as leading edge nicks must be repairable to minimize scrappage.

The STF 429 HPC is a cantilevered stator, drum rotor, and axially split case design, making it structurally different from the HPC's of the other engines. The repairability and mean time between repair of the STF 429 HPC were assumed to be consistent with the other engines. The maintenance material cost per repair was assumed to be 25% higher than the other engines to account for more extensive secondary damage that might occur after a blade or stator failure. The sensitivity factors show the repairability assumption to be very sensitive and definitely in need of further

consideration. Perhaps the axially split case and other features of the design can be shown to reduce the labor manhours per repair significantly. The mean time between repair and maintenance material cost per repair assumptions are about average in sensitivity and probably require further consideration as well. For example, it may be possible to design cantilevered stators to absorb secondary impact with minimum damage.

3. Total Predicted Mature Propulsion System Maintenance Cost:

The total mature propulsion system maintenance cost is therefore the sum of the line maintenance and shop maintenance cost estimates as follows:

<u>Predicted Mature Propulsion System Maintenance Costs</u>		
	Material, O.S.S. and Labor	
	(Basis) <u>Direct Labor Rate</u>	(Basis) <u>Fully Allocated Labor Rate</u>
Line Maintenance (\$/EFH)	\$ 2.11	\$ 5.04
Shop -Installation (\$/EFH)	3.60	7.11
Shop - Basic Engine (\$/EFH)	46.91	56.61
	<hr/>	<hr/>
Total \$/EFH	\$ 52.62	\$ 68.76
 Total Labor \$/EFH	 7.80	 23.94
Total Material \$/EFH	41.36	41.36
Total O.S.S. \$/EFH	3.46	3.46

The cost to maintain the propulsion system during its' introduction into service is addressed in the following beginning' on page 248.

All Temperatures, Pressures & Speeds at SLTO Hot Day (90°F)

Rotor Speed (RPM)		Temperatures (°R)	
Low Rotor (N_1)	4,821	Fan/LPC Exit	675
High Rotor (N_2)	12,150	HPC Exit	1,462
Diameter (inches)		Combustor Exit/HPT Inlet	3,137
1st Stg. Fan Blade Tip	56.74	HPT Exit/LPT Inlet	2,255
1st Stg. LPC Blade Tip	N.A.	Pressures (lb/in ²)	
1st Stg. HPC Blade Tip	24.76	Fan Inlet	14.7
1st Stg. HPT Blade Tip	25.70	LPC Exit	27.84
Mean LPT Blades Tip	33.23	HPC Exit	341.4
# Stages		Combustor Exit/HPT Inlet	321.2
Fan	2	HPT Exit/LPT Inlet	88.4
LPC	N.A.	LPT Exit	22.2
HPC	10	Prime High Cost Parts Prices (\$)	
HPT	2	Fan/LPC	226,880
LPT	4	HPC	127,620
		Diffuser	12,309
		Combustor	44,411
		HPT	184,340
		LPT	184,340

Figure IV-15. STF 429 Engine Parameters Needed for Predicting Its Maintenance Cost

<u>MODULE</u>	<u>AVERAGE MANHOURS PER REPAIR</u>			
	<u>JT3D</u>	<u>JT8D</u>	<u>JT9D-3A</u>	<u>STF 429</u>
FAN/LPC	400	298	302	190
HPC	216	321	440	445
DIFFUSER	474	420	167	150
COMBUSTOR	157	134	258	258
HPT	124	66	261	205
LPT	278	242	312	325

Figure IV - 16 Average Manhours Per Repair For JT3D, JT8D, JT9D and STF 429 Modules

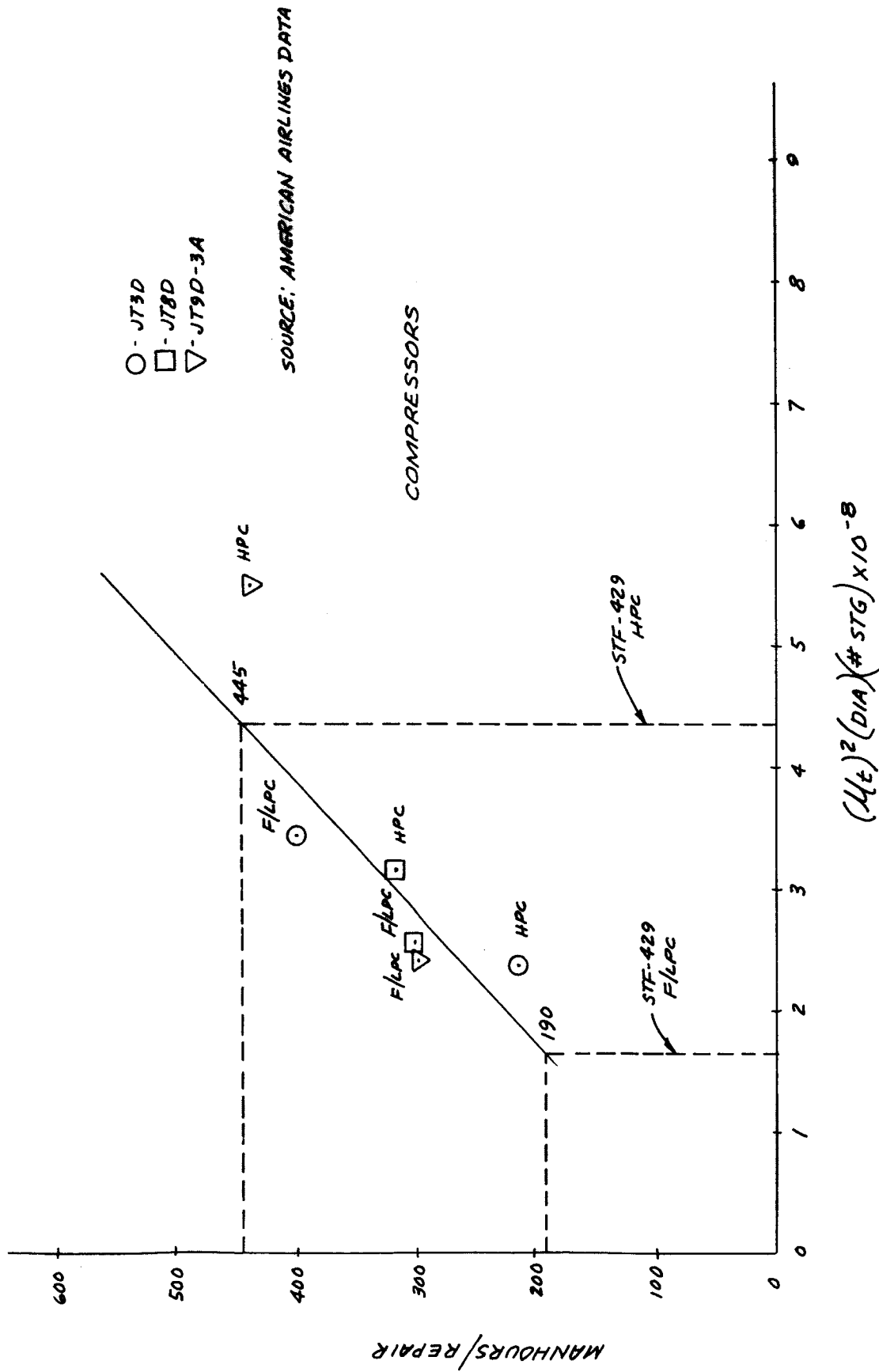


Figure IV -17 . Manhours Per Repair for STF 429 Fan and High Compressor Modules

- JT8D LESS COMPLEX THAN JT3D - ACCESSORY DRIVE NOT IN DIFFUSER.
- JT9D DESIGN IS LESS COMPLEX THAN JT3D AND JT8D.
 - ONLY 1 BEARING IN COMPARTMENT
 - NO OIL SCAVANGE PUMP
 - INTEGRAL STRUTS STANDUPS-ELIMINATES FILLET WELDS
- STF-429 IS LESS COMPLEX THAN JT3D, JT8D AND JT9D.
 - ONLY 1 BEARING IN COMPARTMENT.
 - USES COMPRESSOR EXIT VANES FOR SUPPORTS.
 - BOLTED RATHER THAN WELDED CONSTRUCTION
 - SMALLER THAN JT9D

SOURCE: AMERICAN AIRLINES DATA

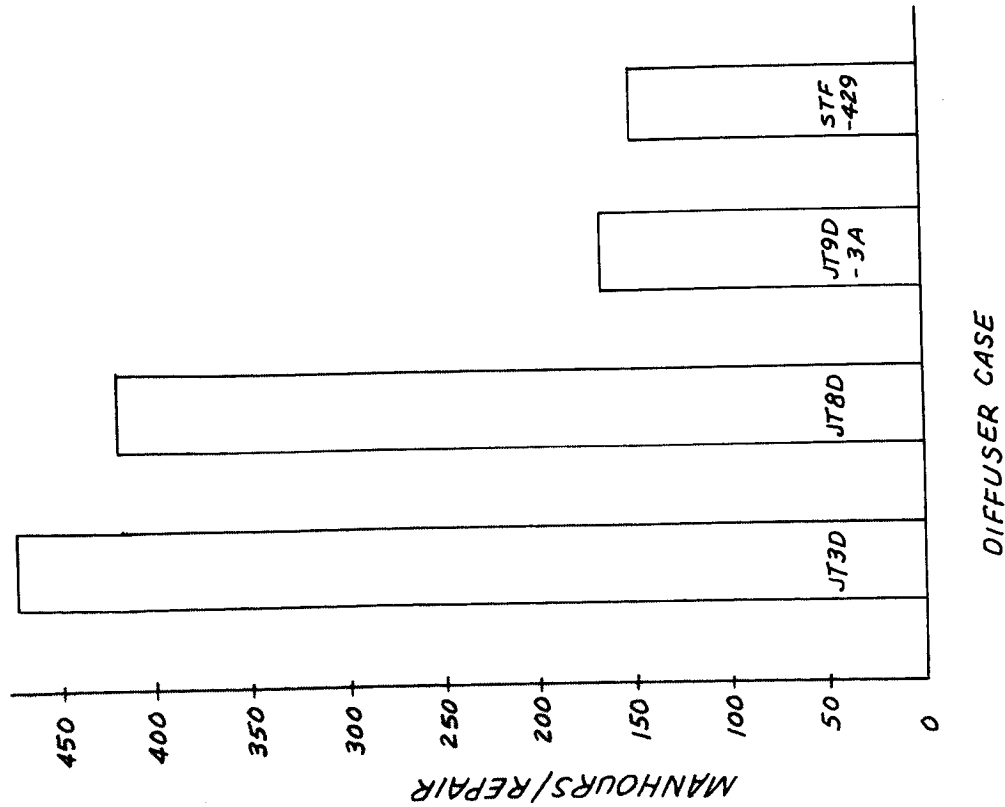


Figure IV - 18. Manhours Per Repair for STF 429 Diffuser Section

- JT3D USES CAN- ANNULAR COMBUSTORS THAT ARE MORE COMPLEX AND LARGER THAN THE JT8D CAN-ANNULAR COMBUSTORS.
- JT9D COMBUSTION DISTORTION AND OVALIZATION IS MORE SEVERE DUE TO LARGER SIZE.
- JT9D COMBUSTOR HEAD DESIGN IS A COMPLEX SHEET METAL WELDMENT THAT IS DIFFICULT TO REPAIR.
- STF-429 USES ANNULAR COMBUSTORS WITH FINWALL CONSTRUCTION. SURFACE AREA IS $\approx 1/2$ THAT OF THE JT9D

SOURCE: AMERICAN AIRLINES DATA

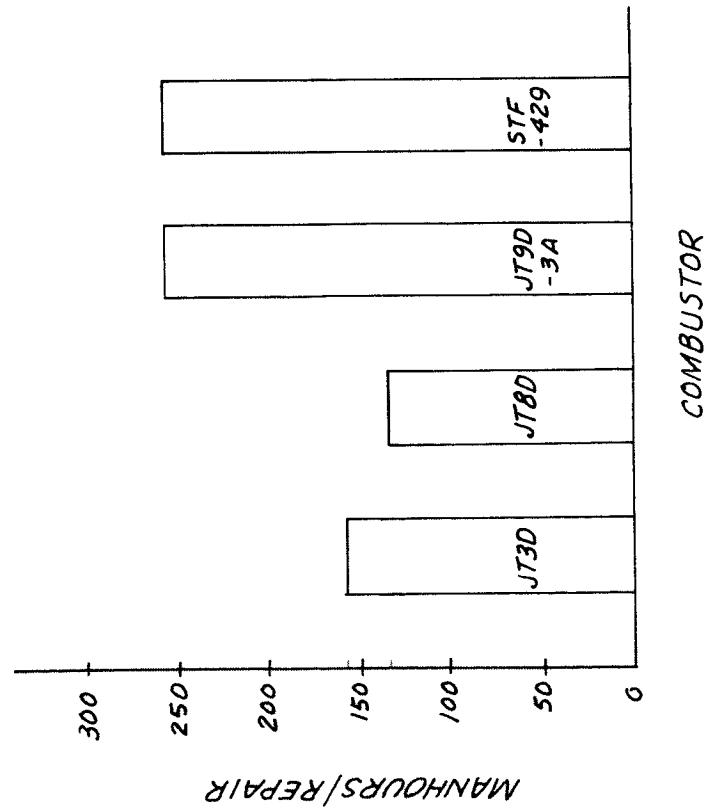


Figure IV -19 . Manhours Per Repair for STF 429 Combustor Section

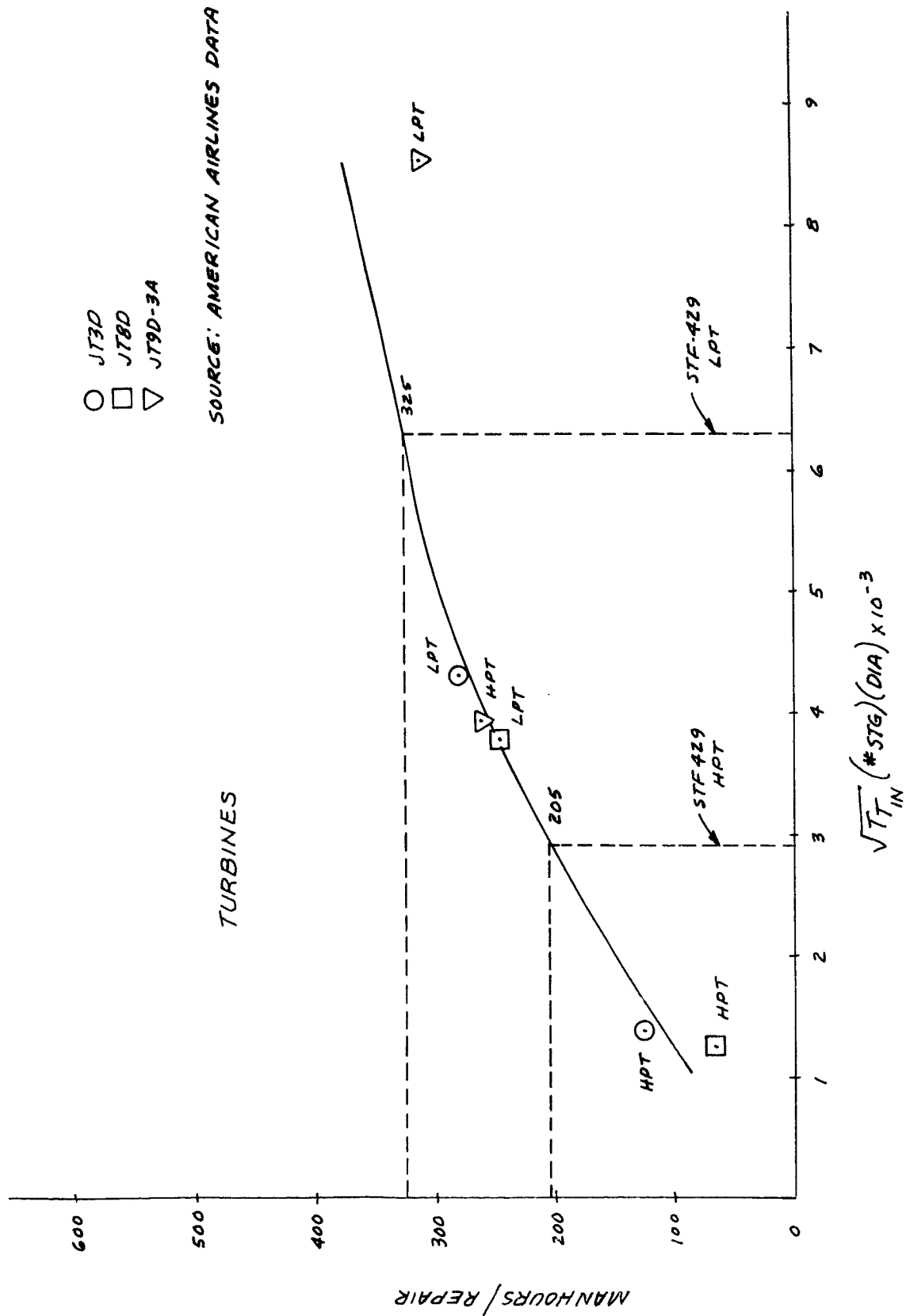


Figure IV -20 . Manhours Per Repair for STF 429 High and Low Turbine Modules

<u>MODULE</u>	<u>MEAN TIME BETWEEN REPAIR</u>		
	<u>JT3D</u>	<u>JT8D</u>	<u>JT9D-3A</u>
			<u>STF 429</u>
FAN/LPC	8586	4848	9480
HPC	4654	3998	3950
DIFFUSER	4981	5050	5925
COMBUSTOR	3209	3222	2844
HPT	4972	4744	2844
LPT	3209	3229	3950
			2680
			2800

NOTE: MATURE ENGINE
1.25 HOUR FLIGHT LENGTH

Figure IV - 21 . Mean Time Between Repair for JT3D, JT8D, JT9D and STF 429 Modules

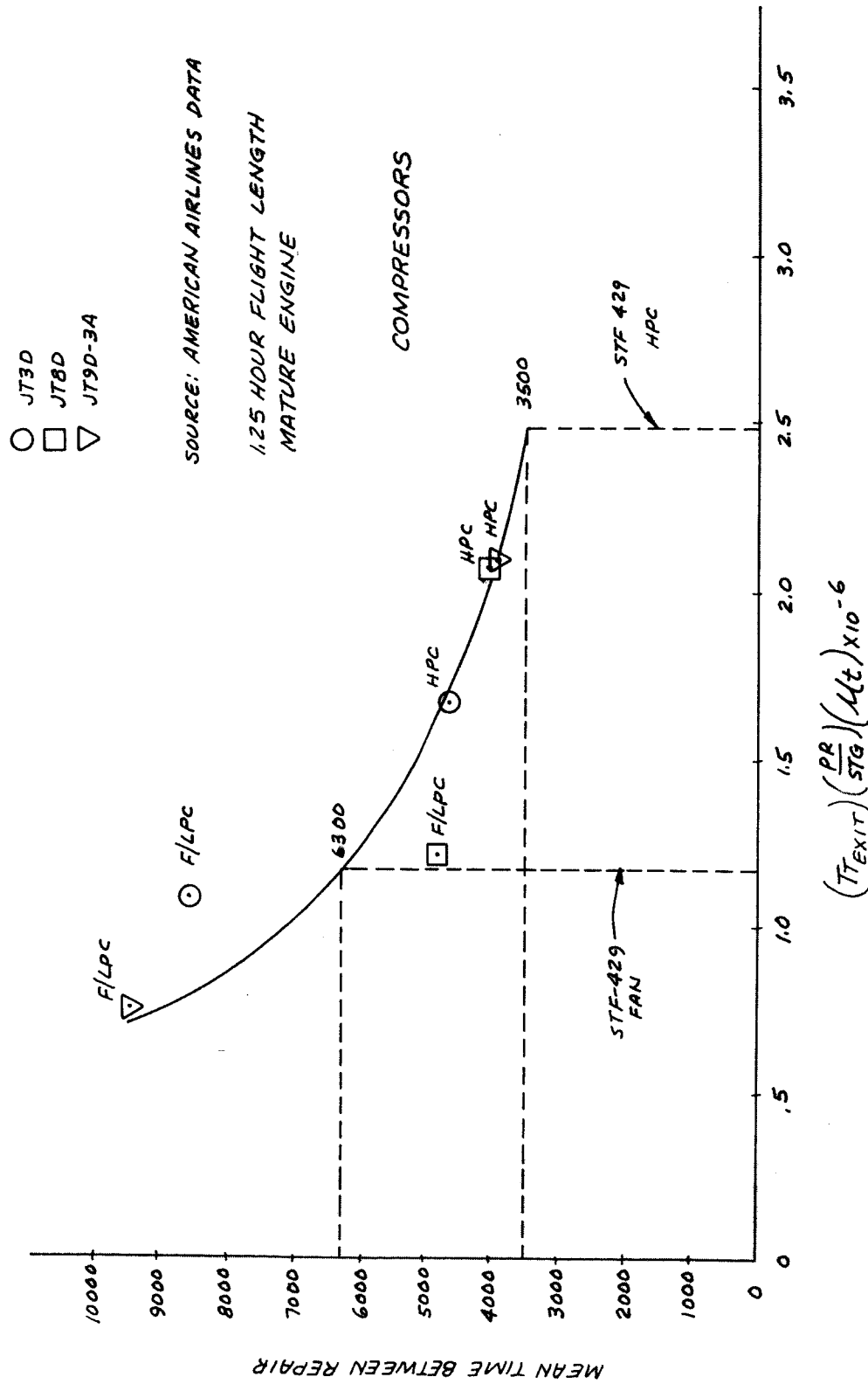


Figure IV - 22 . Mean Time Between Repair for STF 429 Fan and High Compressor Modules

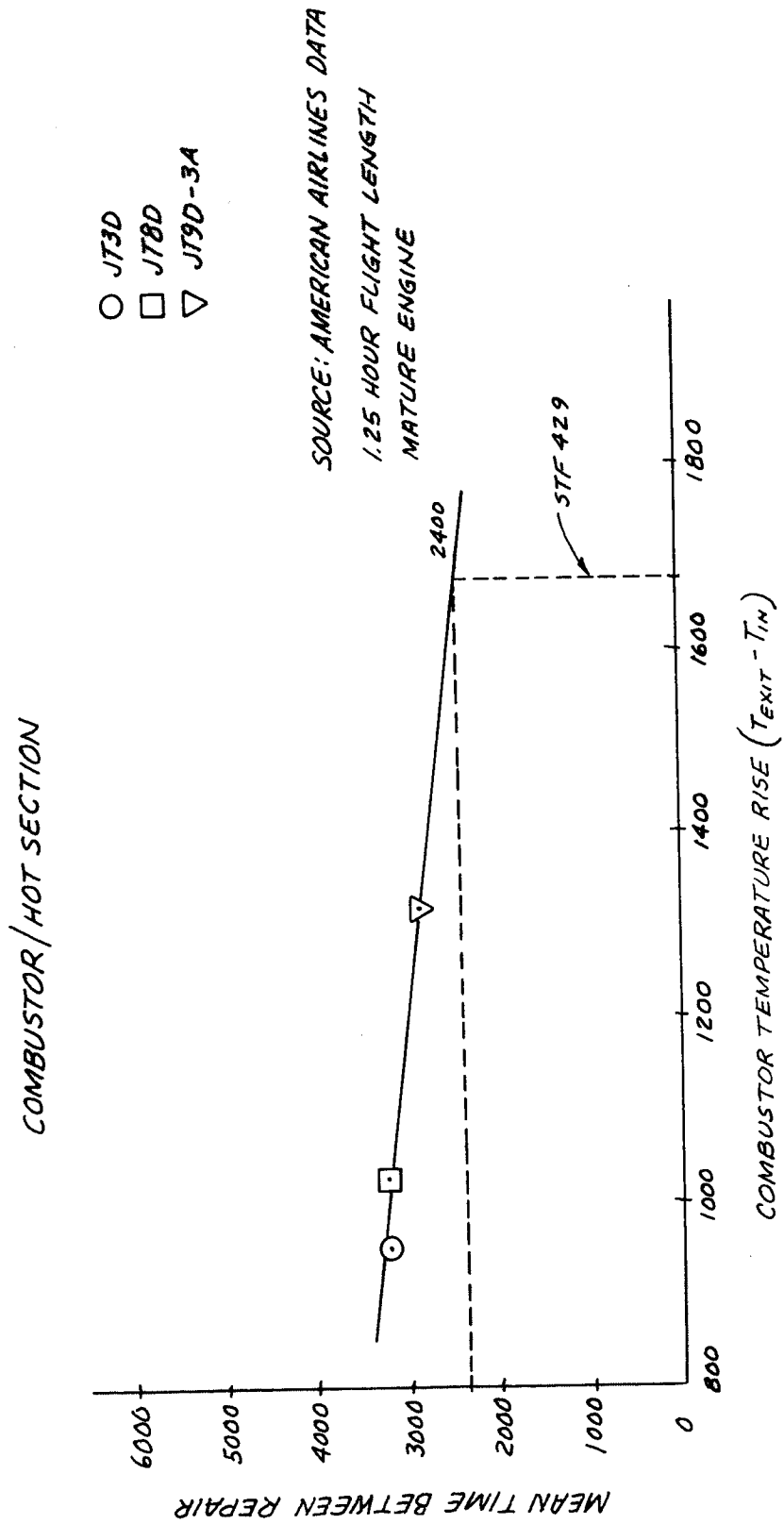


Figure IV - 23. Mean Time Between Repair for STF 429 Combustor Section

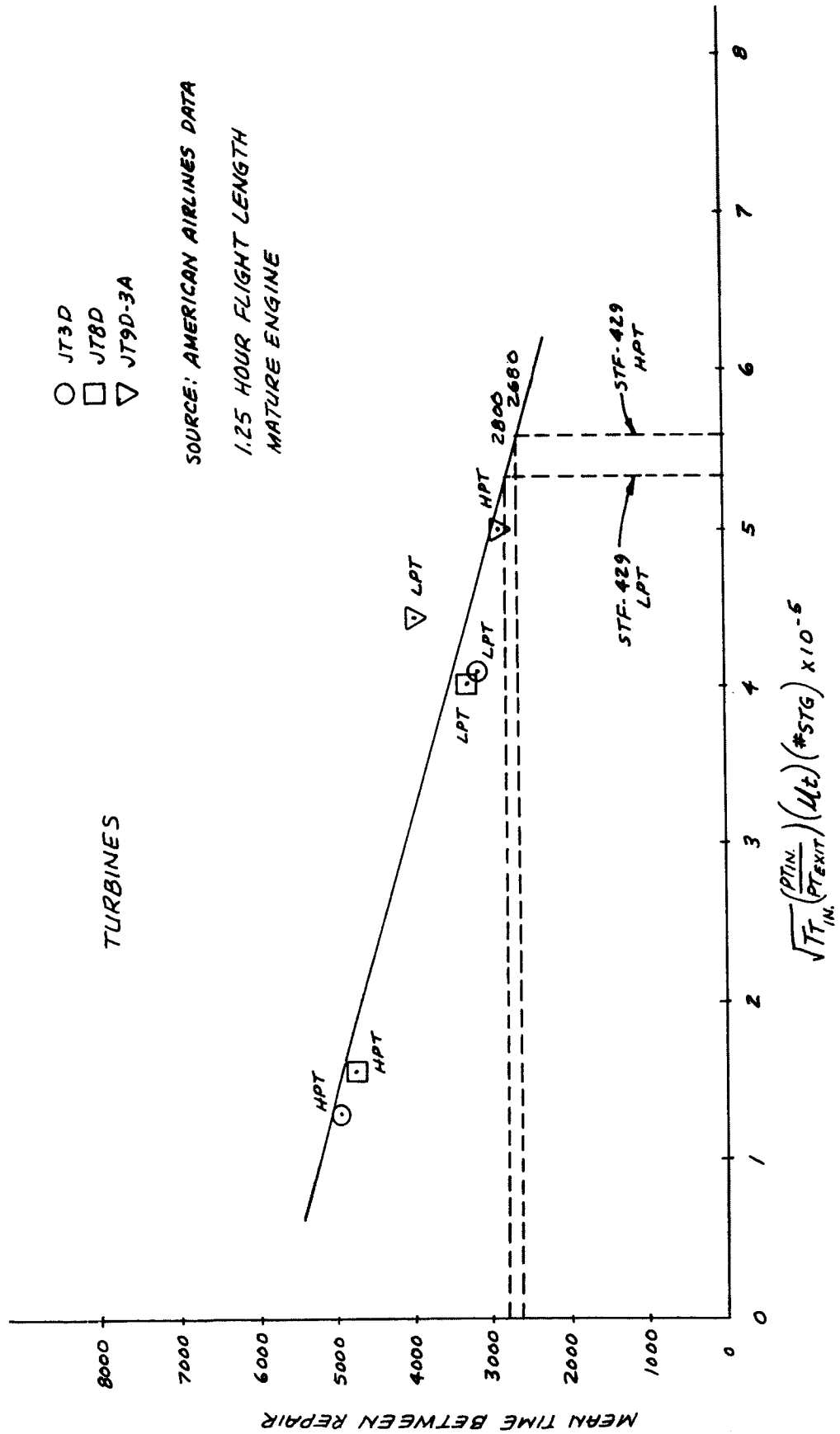


Figure IV - 24 Mean Time Between Repair for STF 429 High and Low Turbine Modules

<u>MODULE</u>	<u>MH/REPAIR</u>	<u>MTBR</u>	<u>MH/EFH</u>	<u>MLC/EFH</u>
FAN/LPC	190	6300	.030	.64
HPC	445	3500	.127	2.73
DIFFUSER	150	5925	.025	.54
COMBUSTOR	258	2400	.108	2.32
HPT	205	2680	.077	1.65
LPT	325	2800	.116	2.49
SUB TOTAL, MAJOR MODULES			.483	10.37
MISC. SECTIONS	-	-	.188	4.03
TOTAL SHOP LABOR (MH/EFH)			.671	\$14.40/EFH

NOTE: MATURE ENGINE
1.25 HOUR FLIGHT LENGTH

Figure IV - 25 . STF 429 Manhour Per Engine Flight Hour

<u>MODULE MMC PER REPAIR/PRICE</u>		
<u>Module/Engine</u>	<u>Typical Past Experience Value*</u>	<u>STF 429</u>
Fan/LPC	.125	.125
HPC	.114	.142
Diffuser	.138	.138
Combustor	.128	.128
HPT	.238	.238
LPT	.089	.089

*Based on Task I Study

Figure IV-26 Maintenance Material Cost Per Repair/Price
for the STF 429 Modules

<u>MODULE</u>	<u>MMC PER REPAIR / PRICE</u>	<u>PRIME HIGH COST PARTS PRICE</u>	<u>MTBR</u>	<u>MMC/EFH</u>
FAN/LPC	.125	\$226,880	6300	4.50
HPC	.142	127,620	3500	5.18
DIFFUSER	.138	12,309	5925	.29
COMBUSTOR	.128	44,411	2400	2.37
HPT	.238	184,340	2680	16.37
LPT	.089	184,340	2800	5.86
6 MODULE TOTAL	-	-	-	34.57
MISCELLANEOUS PARTS	-	-	-	4.18
TOTAL MMC				\$38.75/EFH

Figure IV -27 . Estimated STF 429 Maintenance Material Cost Per
Engine Flight Hour

<u>MAINTENANCE COST</u>	
	<u>\$/EFH</u>
FULLY ALLOCATED LABOR	14.40
MAINTENANCE MATERIAL	38.75
OUTSIDE SERVICES	3.46
<hr/>	
TOTAL MAINTENANCE COST	\$56.61/EFH

MEAN TIME BETWEEN ENGINE REMOVAL

<u>MOST FREQUENTLY REMOVED MODULE</u>	<u>REPAIR INTERVAL</u>
---------------------------------------	------------------------

COMBUSTOR 2400

MTBER = .83X2400 = 1992

ESTIMATED STF 429 MATURE MTBER 2,000 HRS.

Figure IV - 28. STF 429 Total Basic Engine Maintenance Cost and Mean Time Between Engine Removal - Mature Engine

% CHANGE IN TOTAL MAINTENANCE COST FOR 10% CHANGE IN:

<u>MODULE</u>	<u>MANHOURS PER REPAIR</u>	<u>MEAN TIME BETWEEN REPAIR</u>	<u>MAINT. MATERIAL COST PER REPAIR OR MODULE PRICE</u>
FAN/LPC	0.1	1.0	0.9
HPC	0.5	1.5	1.0
DIFFUSER	0.1	0.2	0.1
COMBUSTOR	0.4	1.0	0.6
HPT	0.3	3.4	3.1
LPT	0.5	1.6	1.1

Figure IV-29 Total Maintenance Cost Sensitivity - STF429

b. Maintenance Cost - First Five Years

1. Power Plant Installation

Due to the higher engine removal rate, the first few years of operation of a new engine, as discussed in Paragraph IV C.4.b.2, the power plant installation maintenance costs will be higher.

Using the formulas developed in IV C.4.a.1, the total line direct labor and material and installation shop direct labor and material costs can be predicted for the study aircraft at 1.25 average flight length as follows:

Total Line Direct Labor (LL_T) - Manhours per Engine Flight Hour

a) $2 \text{ (Installation Line Labor) = Total Line Labor (Inst'l + Basic Engine)}$

$$2 \left[LL_{71} + \frac{X}{1.15} (LL_{78} + LL_{80}) + LL_R \right] = LL_T$$

X = Ratio of labor cost at study flight length, Figure IV-13

Subscript numbers represent particular ATA systems and

"R" represents the remaining power plant ATA's excluding 72.

b) $LL_{71} = ERR \times 1.30 \times (MH)$

ERR = Engine Removal Rate per 1000 Engine Flight Hours =
1.10/1000 EH

MH = Manhours for Engine Replacement = 27

1.30 = Factor to Account for Cowl and Some QEC Repair

$$LL_{71} = 1.10/1000 \times 1.30 \times 27 = 0.039 \text{ MH/EH}$$

c) $LL_{78} = N \times 0.020$

N = Number of Thrust Reversers per Engine = 2

$$LL_{78} = 2 \times 0.020 = 0.040 \text{ MH/EH}$$

d) $LL_{80} = 0.006 \text{ MH/EH}$

e) $LL_R = ERR \times 75$

$$LL_R = 1.10/1000 \times 75 = 0.083 \text{ MH/EH}$$

f) $LL_T = 2 \left[0.039 + \frac{1.15}{1.15} (0.040 + 0.006) + 0.083 \right] = 0.336 \text{ MH/EH}$
 $= 0.336 \times 7.00 = \$2.35/\text{EH or } \$7.05/\text{FH}$

Total Line Material (LM_T) - 1972 Dollars per Engine Flight Hour

a) $LM_T = 0.00133 \times \text{Engine Price} \times ERR$

ERR = 1.10/1000 EH

Engine Price = \$1,050,000

$$LM_T = \frac{0.00133 \times 1,050,000 \times 1.10}{1000} = \$1.53/\text{EH or } \$4.59/\text{FH}$$

3. Installation Shop Direct Labor (SL Instl) - Manhours per Engine Flight Hour

$$a) \quad SL_{71} + \frac{X}{1.15} (SL_{78} + SL_{80}) + SL_R = SL \text{ Instl}$$

$$b) \quad SL_{71} = ERR \times 1.30 \times (MH)$$

$$ERR = \text{Engine Removal Rate Per 1000 Engine Flight Hours} = 1.10/1000/EH$$

$$MH = \text{Manhours for QEC Build-up and Tear-down} = 140 + 30 = 170$$

$$1.30 = \text{Factor to Account for Cowl and Some QEC Repair}$$

$$SL_{71} = 1.10/1000 \times 1.30 \times 170 = 0.242 \text{ MH/EH}$$

$$c) \quad SL_{78} = N \times 0.04$$

$$N = \text{Number of Thrust Reversers per Engine} = 2$$

$$SL_{78} = 2 \times 0.04 = 0.08 \text{ MH/EH}$$

$$d) \quad SL_{80} = 0.014 \text{ MH/EH}$$

$$e) \quad SL_R = ERR \times 75$$

$$SL_R = 1.10/1000 \times 75 = 0.083 \text{ MH/EH}$$

$$f) \quad SL \text{ Instl} = 0.242 + \frac{1.15}{1.15} (0.080 + 0.014) + 0.083 = 0.419 \text{ MH/EH} \\ = 0.419 \times 7.00 = \$2.93/EH \text{ or } \$8.79/FH$$

4. Installation Shop Material (SM Instl) - 1972 Dollars per Engine Flight Hour

$$a) \quad SM_{71} + \frac{Y}{1.19} (SM_{78} + SM_{80}) + SM_R = SM \text{ Instl}$$

$$Y = \text{Ratio of Material Costs at Study Flight Length, Fig. IV- 14}$$

$$b) \quad SM_{71} = 0.0015 \times \text{Engine Price} \times ERR$$

$$SM_{71} = \frac{0.0015 \times 1,050,000 \times 1.10}{1000} = \$1.73/EH$$

$$c) \quad SM_{78} = N \times \$0.30$$

$$N = \text{Number of Thrust Reversers per Engine} = 2$$

$$SM_{78} = 2 \times 0.30 = \$0.60/EH$$

$$d) \quad SM_{80} = \$0.15/EH$$

$$e) \quad SM_R = 0.0007 \times \text{Engine Price} \times ERR$$

$$SM_R = \frac{0.0007 \times 1,050,000 \times 1.10}{1000} = \$0.81/EH$$

$$f) \quad SM_{Instl} = 1.73 + \frac{1.19}{1.19} (0.60 + 0.15) + 0.81 = \$3.29/EH \text{ or } \$9.87/FH$$

2. Basic Engine

During the first few years of operation of a new engine in the field, maintenance material and labor costs are significantly higher than they are for the mature engine. It is during the early years that the effects of problems that were undetected during development testing are discovered and corrected. Also, acceptance and repair standards for damaged parts are not thoroughly defined during this period because of the lack of operating experience. This leads to scrappage rates which are high relative to mature values. As operating experience is built up, the limits are defined and repair procedures developed which in turn will lower the maintenance cost of the engine. This is all part of the maturing process. The rate at which this maturing occurs depends on the rate of buildup of experience for the entire fleet, not just the one operator's engines. The rate at which airplanes are built and how they are utilized are also important factors in the maturing process. The early maintenance labor and material cost peaks are illustrated clearly on Figures III-9 and III-30.

Maintenance Labor Cost

The first five year average MH/EFH for the STF 429 engine (Figure IV-30) was estimated by applying factors to the mature engine repair rate and manhours per repair. These factors were derived from JT3D, JT8D and JT9D experience in Section III.

For the repair rate, a factor of 2.2 times the mature rate (0.50) appears to be a reasonable estimate. This factor gives an average STF 429 repair rate for the first five years of 1.10 per 1000 engine flight hours. This is a mean time between removal of 910 hours (Figure IV-30).

For the manhours per repair value, a factor of 70% of the mature value (1340) was used. This yields a value of 940 manhours per repair for the STF 429 engine during the first five years of commercial service.

The predicted MH/EFH for the first five years is calculated by dividing the manhours per repair by the mean time between repair. The MH/EFH value for the initial operations of the STF 429 is $\frac{940}{910}$ or 1.03 (compared to a mature value of .671 MH/EFH). Using a fully allocated labor rate of \$21.47 per manhour (1972 rates), this is equivalent to \$22.10 per engine flight hour.

Maintenance Material Cost

The first five year average maintenance material cost of the STF 429 is estimated by applying two factors to the mature MMC/EFH estimate. One factor adjusts the MMC per Repair/Price and the other adjusts the MTBR. The MMC per Repair/Price factor was found in Section III to average 0.75. The MTBR factor is 2.2 as described in C.4.b.2.1 above. Hence, the STF 429 first five year estimated MMC = \$64.00 per engine flight hour as shown on Figure IV-30

Total Basic Engine Maintenance Cost - First Five Years

The total basic engine maintenance cost for the first five years (Figure IV-30) also comprises labor, material and outside service charges. Outside service charges are assumed to be 6% of the total maintenance cost as for the mature engine. Hence the total maintenance cost for the first five years for the 1.25 hour flight cycle length is \$91.70/EFH as shown in Figure IV-30

<u>MAINTENANCE COST</u>			
	<u>MATURE ENGINE</u>	<u>MULTIPLICATION FACTORS</u>	
		<u>MTBER</u>	<u>COST/REPAIR</u>
FULLY ALLOCATED LABOR	14.40	2.2	.70
MAINTENANCE MATERIAL	38.75	2.2	.75
OUTSIDE SERVICES	3.46	-	-
			5.60
			<u>22.10</u>
			64.00
			5.60
			<u>5.60</u>
TOTAL MAINTENANCE COST			\$91.70/EFH

<u>MEAN TIME BETWEEN ENGINE REMOVAL (MTBER)</u>		
<u>MATURE ENGINE</u>	<u>MULTIPLICATION FACTOR</u>	<u>FIRST 5 YEARS</u>
2000	1/2.2	910
	ESTIMATED MTBER = 910 HOURS	

Figure IV - 30 STF 429 Total Basic Engine Maintenance Cost and Mean Time Between Engine Removal - 1st 5 Years

3. Predicted Average Propulsion System Maintenance Cost in Early Service.

The average maintenance cost per engine flight hour for the propulsion system during the first five years of service is the sum of both the line and shop cost estimates as shown below:

Predicted Average Propulsion System Maintenance Costs in Early Service

Material, O.S.S. and Labor

		(Basis) Direct Labor Rate	(Basis) Fully Allocated Labor Rate
Line Maintenance	\$/EFH	3.88	8.75
Shop Installation	\$/EFH	6.22	12.29
Shop Basic Engine	\$/EFH	<u>76.80</u>	<u>91.70</u>
Total	\$/EFH	86.90	112.74
Total Labor	\$/EFH	12.48	38.32
Total Material	\$/EFH	68.82	68.82
Total O.S.S.	\$/EFH	5.60	5.60

5. Predicted Mature Propulsion System Direct Operating Cost

Propulsion system direct operating cost is the sum of the depreciation, fuel and maintenance costs. The table presented below summarized the predicted direct operating cost elements of the selected design developed in the preceding analysis.

Summary of Direct Operating Cost
Per Aircraft Operating Hour

	<u>\$/FH</u>	<u>\$/BH</u>
<u>Depreciation</u>		
-Propulsion	\$106.20	\$ 88.50
-Spares	24.64	20.53
	<u>\$130.84</u>	<u>\$109.03</u>
Fuel	324.45	270.38
Mature Maintenance (Labor Fal.)	206.28	171.90
	<u>\$661.57</u>	<u>\$ 551.31</u>

The estimated total aircraft direct operating cost was determined to be \$1420 per flight hour. The selected propulsion systems' portion of the direct operating cost is equal to 46.6% of this total. It should be noted that at the selected 18¢/gal. fuel price, the sum of the depreciation and mature maintenance costs, is approximately equal to the fuel cost per operating hour. The objectives for advanced technology programs should be directed at reducing the total operating cost. The opportunities to do so are numerous and are addressed in Section VI of this report.

D. Dispatch Reliability Impact

In average operator service it is estimated the mature airplane will provide a 98.0% probability of starting and completing the typical flight shown in Figure III-31 without a delay greater than fifteen (15) minutes due to airplane technical problems. The airplane is assumed to be mature when production airplanes have accomplished at least 400,000 flight hours and at least 260,000 scheduled departures in revenue service. Figure IV-31 illustrates the probable growth of the Mechanical Schedule Reliability for the study airplane.

The 727 historical data is used as a basis for allocating the mature D4-179C airplane interruption rate of 2.0/100 departures (2.0%) between the airframe and propulsion system and in the propulsion system between basic engine and installation. This results in 1.5/100 departures for airframe, 0.5/100 departures for power plant and 0.25/100 departures for basic engine and 0.25/100 departures for installation.

To determine the interruption costs it is assumed that the D4-179C costs per seat-mile will be no greater than the 727 costs per seat-mile. The D4-179C interruption costs are therefore arrived at by adjusting the 727 interruption costs by the ratio of seats (181 seats for the D4-179C and 117 seats for the 727), since the average flight lengths are the same. See Table in Figure III-66

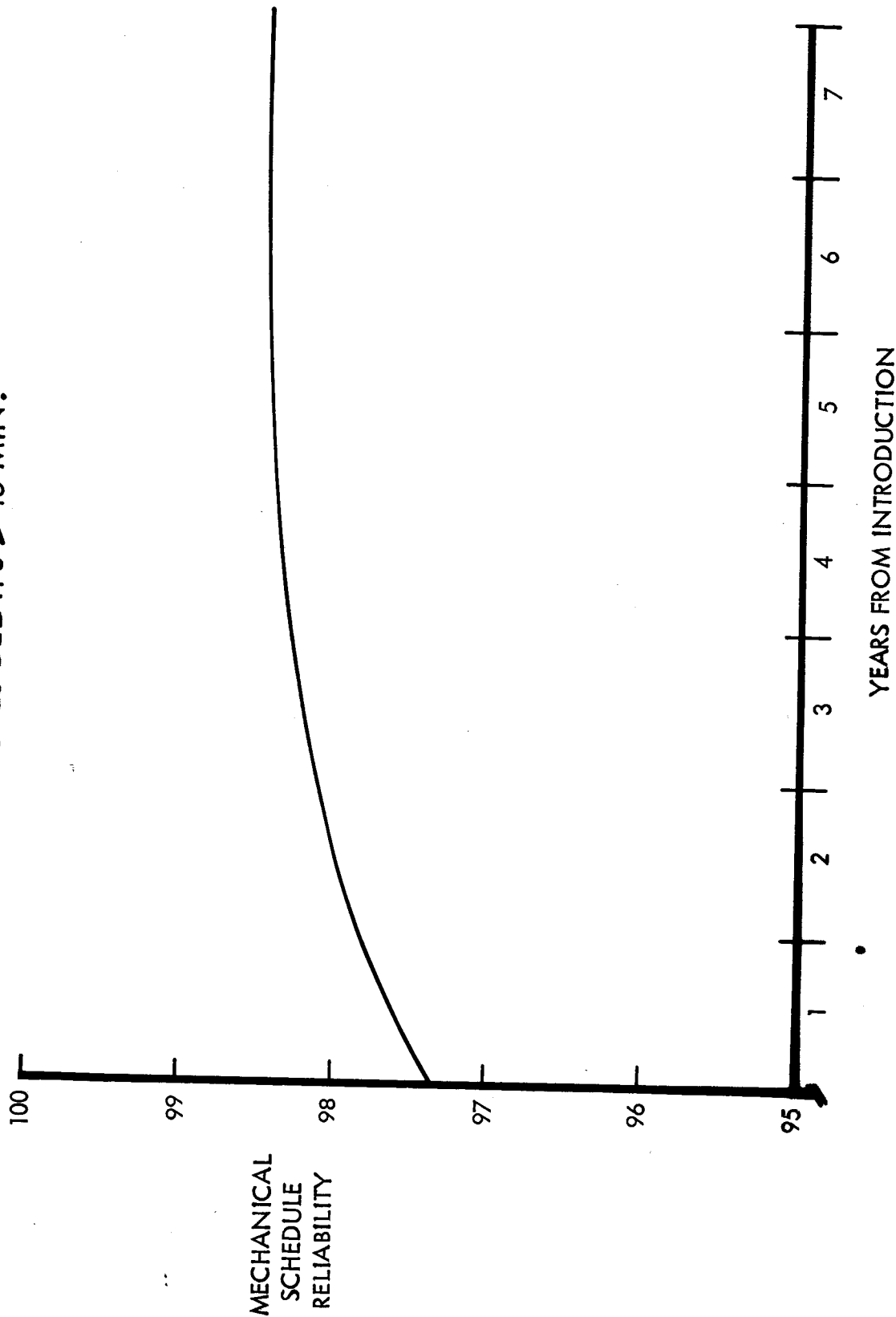
INTERRUPTION COSTS 1972 DOLLARS		
ITEM	727	D4-179C
16-29	88	136
30-59	218	337
60 & Up	978	1513
Cancel.	1272	1968

It is further assumed that the delay time distribution and frequency of cancellations for the power plant system on the D4-179C will be the same as for the power plant system on the 727. Therefore, the interruption costs for the mature D4-179C power plant

MECHANICAL SCHEDULE RELIABILITY

(D4 - 179C AIRPLANE)

- INCLUDES DELAYS > 15 MIN. -



4-3-74

FIGURE IV - 31

system are predicted to be \$384/100 departures with \$169/100 departures being charged to the installation. This is computed as follows:

Total Power Plant System Calculation

$$\frac{\text{D4-179C Power Plant I.R.}}{727} \times \frac{\text{D4-179C Seats}}{727} \times 727 \text{ Power Plant I.C.} = \text{D4-179C Power Plant I. C.}$$

I.R. = Interruption Rate per 100 Departures

I.C. = Interruption Cost per 100 Departures

$$\frac{0.5}{0.635} \times \frac{181}{117} \times \$315/100 \text{ Departures} = \$384/100 \text{ Departures}$$

Installation Calculation

$$\frac{\text{D4-179C Instl. I.R.}}{727} \times \frac{\text{D4-179C Seats}}{727} \times 727 \text{ Instl. I.C.} = \text{D4-179C Instl. I.C.}$$

$$\frac{0.250}{0.320} \times \frac{181}{117} \times \$140 = \$169/100 \text{ Departures}$$

E. Comparison with Actual Experience of Current Propulsion Systems

The STF 429 predicted maintenance cost elements can be combined at various levels for comparison with the actual experience of the JT3D, JT8D and JT9D. Four different levels, which have particular significance to the general problem of maintenance cost estimating, are presented below.

Figures IV-32, 33 and 34 provide visibility of the three major factors of total maintenance cost as it was analyzed for the STF 429. These factors are labor manhours per repair, removal rate and material cost per repair (normalized by engine price). These figures generally show the STF 429 predictions to be reasonable in comparison with experience; the differences were explained as the STF 429 predictions were built-up.

Figures IV-35 and 36 separate the total maintenance cost into labor man-hours per engine flight hour and material cost per engine flight hour (normalized by engine price). A similar breakdown is used in the ATA method. A major disadvantage of this approach is the lack of visibility of the engine removal rate influence.

Figure IV-37 presents the total maintenance cost per repair (normalized by engine price) which combines with removal rate (Figure IV-18) to give total cost per engine flight hour. This is the simplest form that retains visibility of the removal rate influence, but it sacrifices visibility of the material-labor split.

Figure IV-38 presents total maintenance cost per engine hour (normalized by engine price). The reasonable agreement among the mature JT3D, JT8D and predicted STF 429 costs on this figure suggests a simple rule-of-thumb method of estimating maintenance cost.

The rule is: mature maintenance cost = \$5 per engine hour for each \$100,000 of engine price for engines operating at their design flight length. This cost includes the fully allocated labor, material and outside services expended on the basic engine in the maintenance shop.

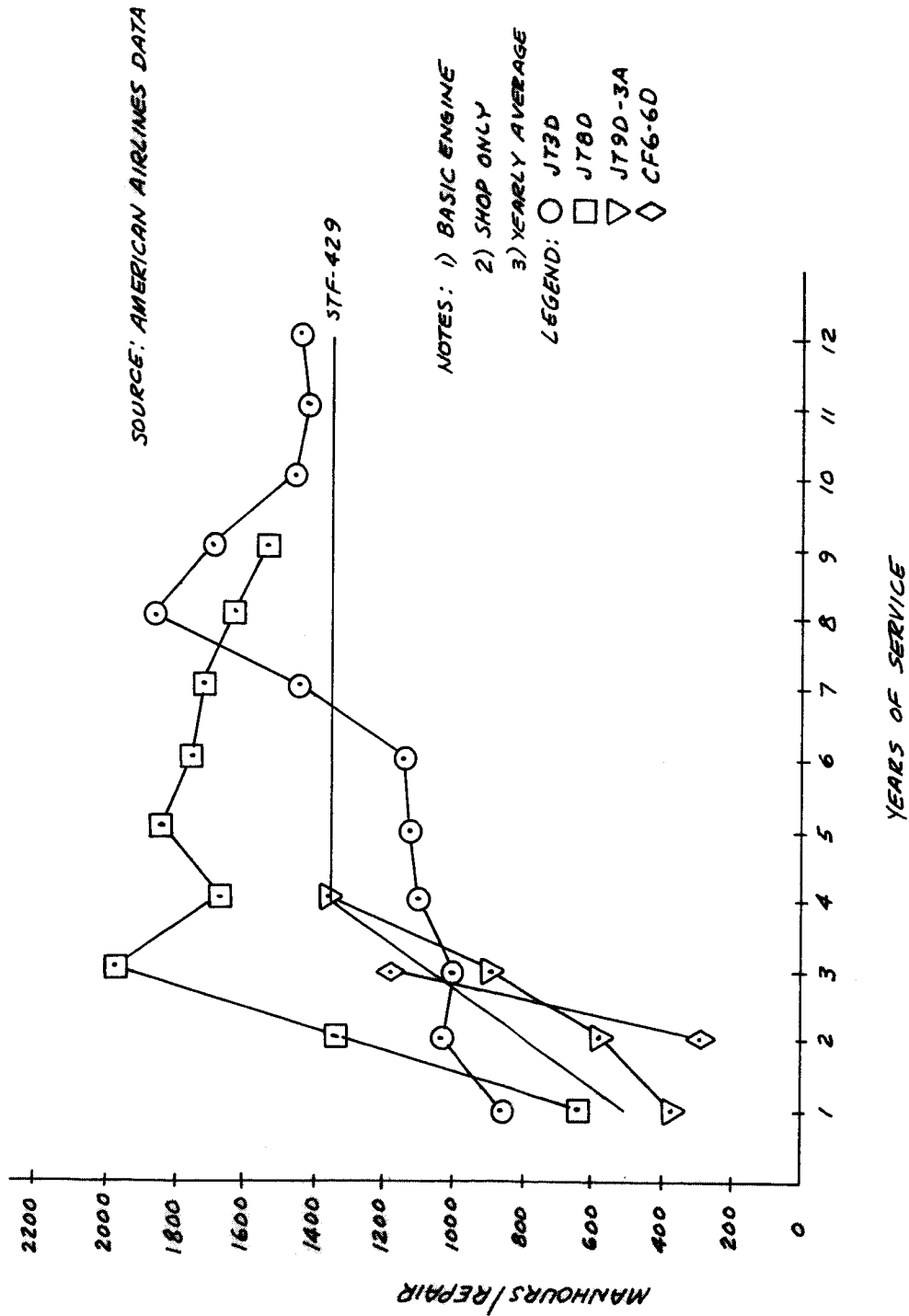


Figure IV- 32 Comparison of Estimated STF 429 Manhours Per Repair With JT3D, 8D, and 9D Experience

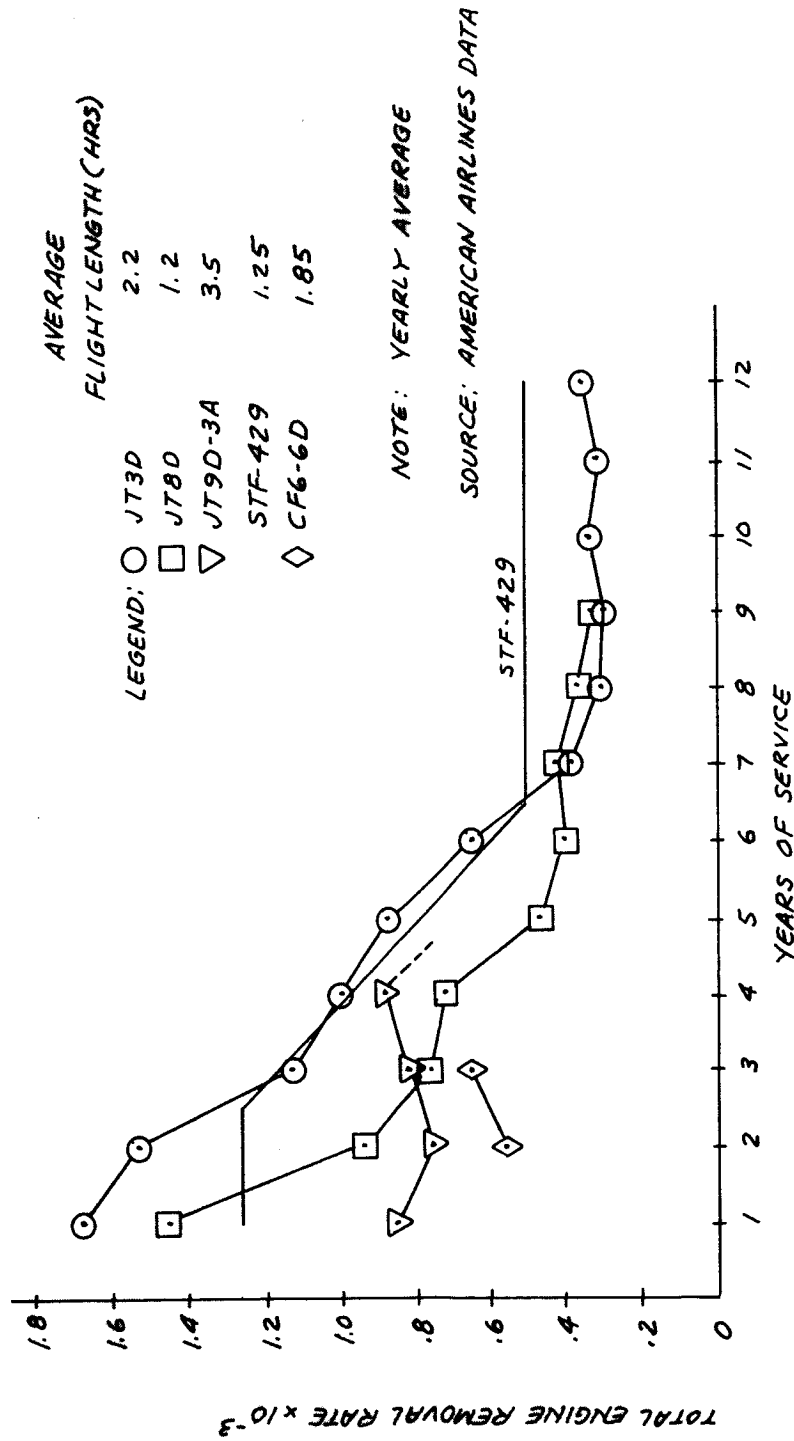


Figure IV-33 Comparison of Estimated STF 429 Engine Removal Rate With JT3D, JT8D and JT9D Experience

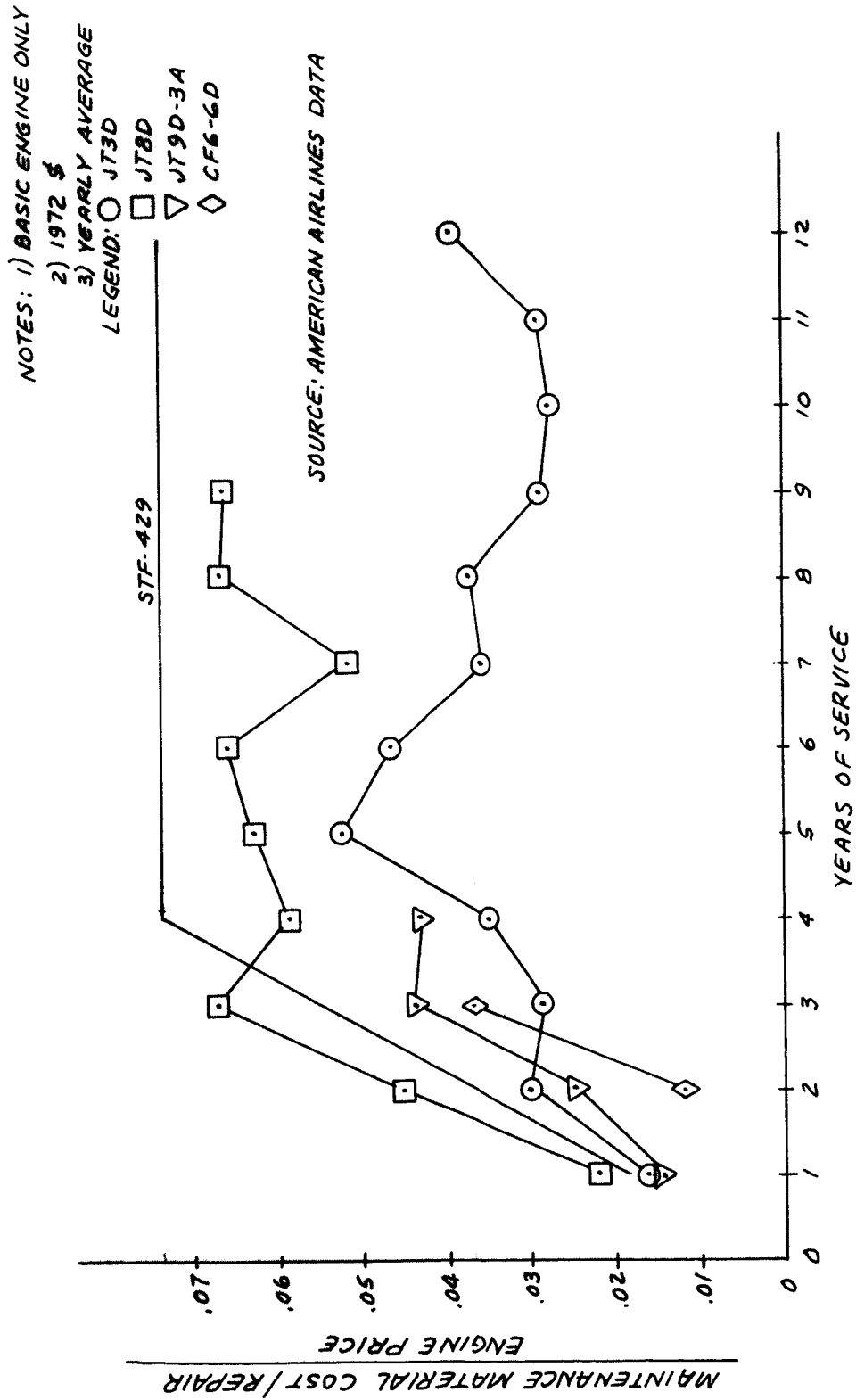


Figure IV-34 Comparison of Estimated STF 429 Maintenance Material Cost Per Repair, Normalized for Engine Price, With JT3D, JT8D and JT9D Experience

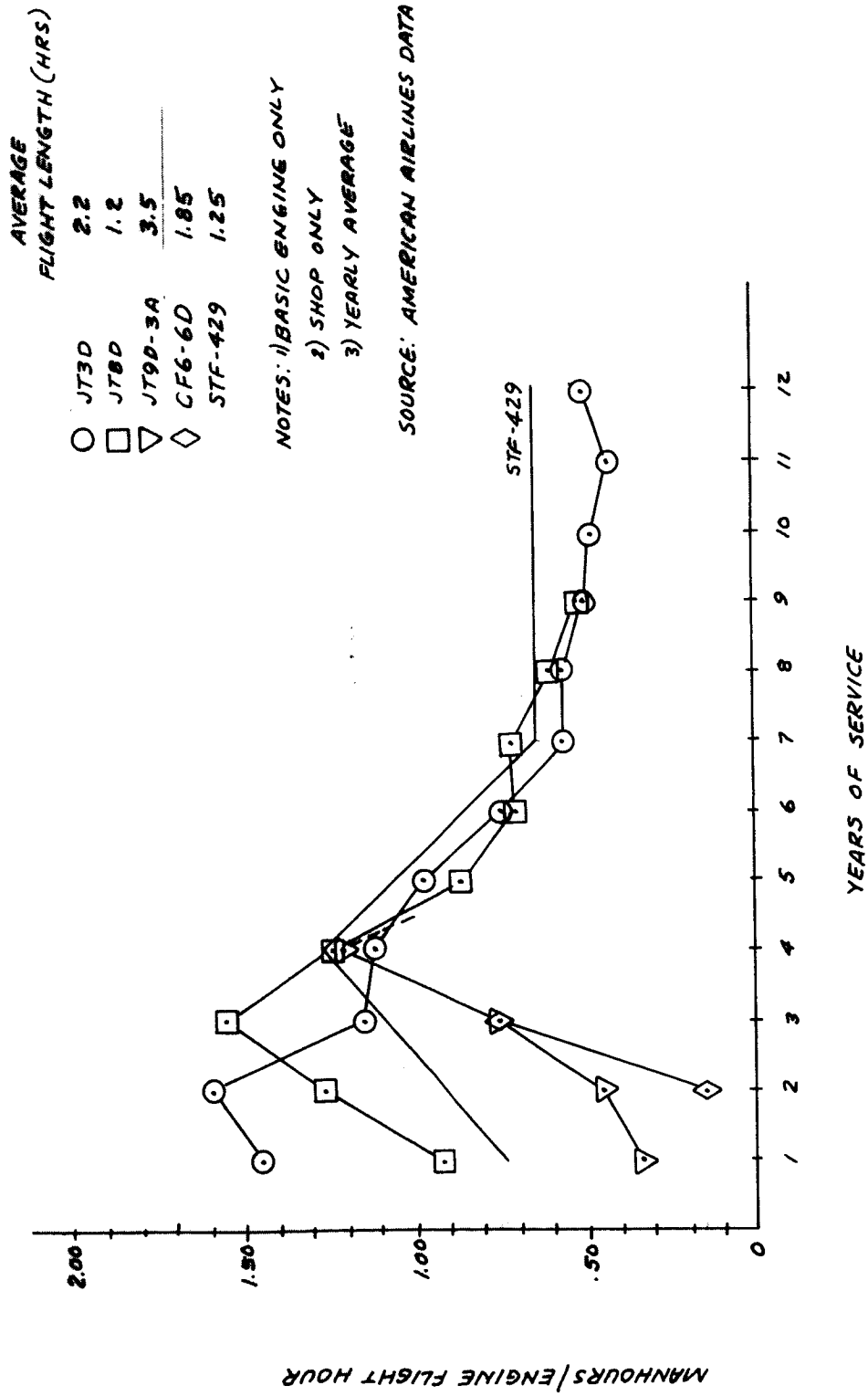


Figure IV- 35 Comparison of Estimated STF 429 Manhour Per Engine Flight Hour With JT3D, JT8D, and JT9D Experience

NOTES: 1) BASIC ENGINE ONLY

2) 1972 \$

3) YEARLY AVERAGE

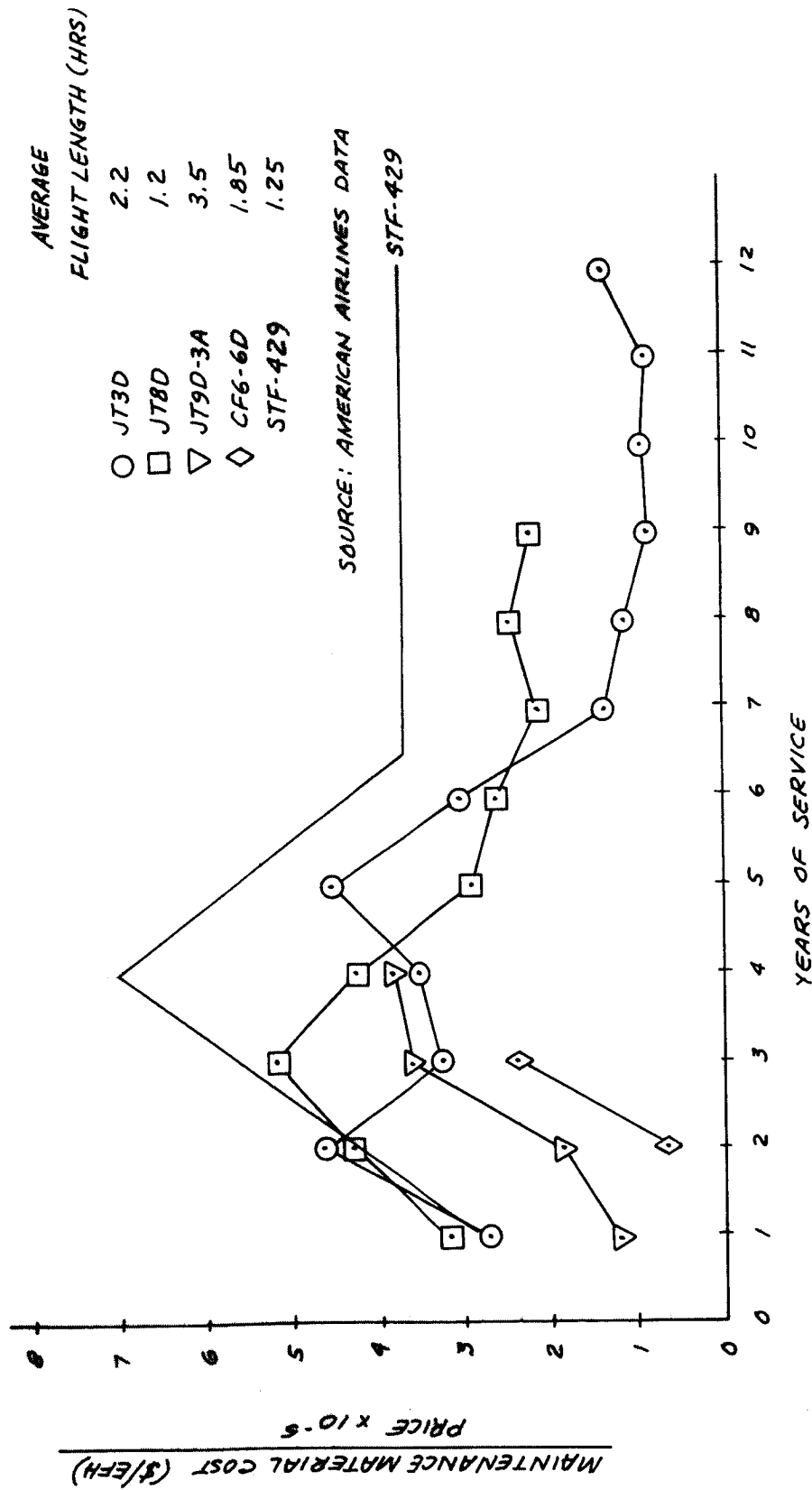


Figure IV-36 Comparison of Estimated STF 429 Maintenance Material Cost, Normalized for Engine Price, With JT3D, JT8D and JT9D Experience

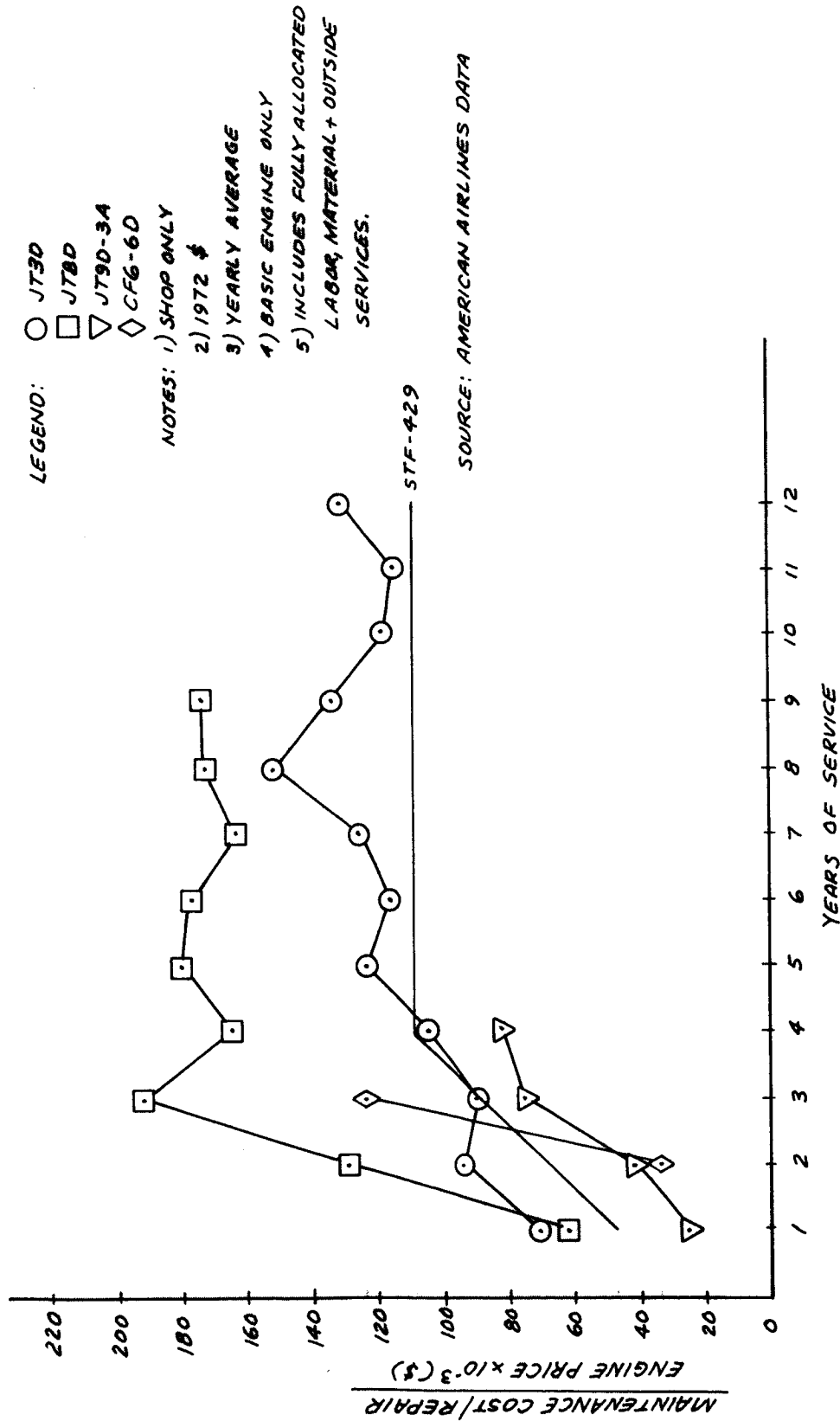


Figure IV-37 Comparison of Total Estimated STF 429 Maintenance Cost Per Repair, Normalized for Engine Price, With JT3D, JT8D and JT9D Experience

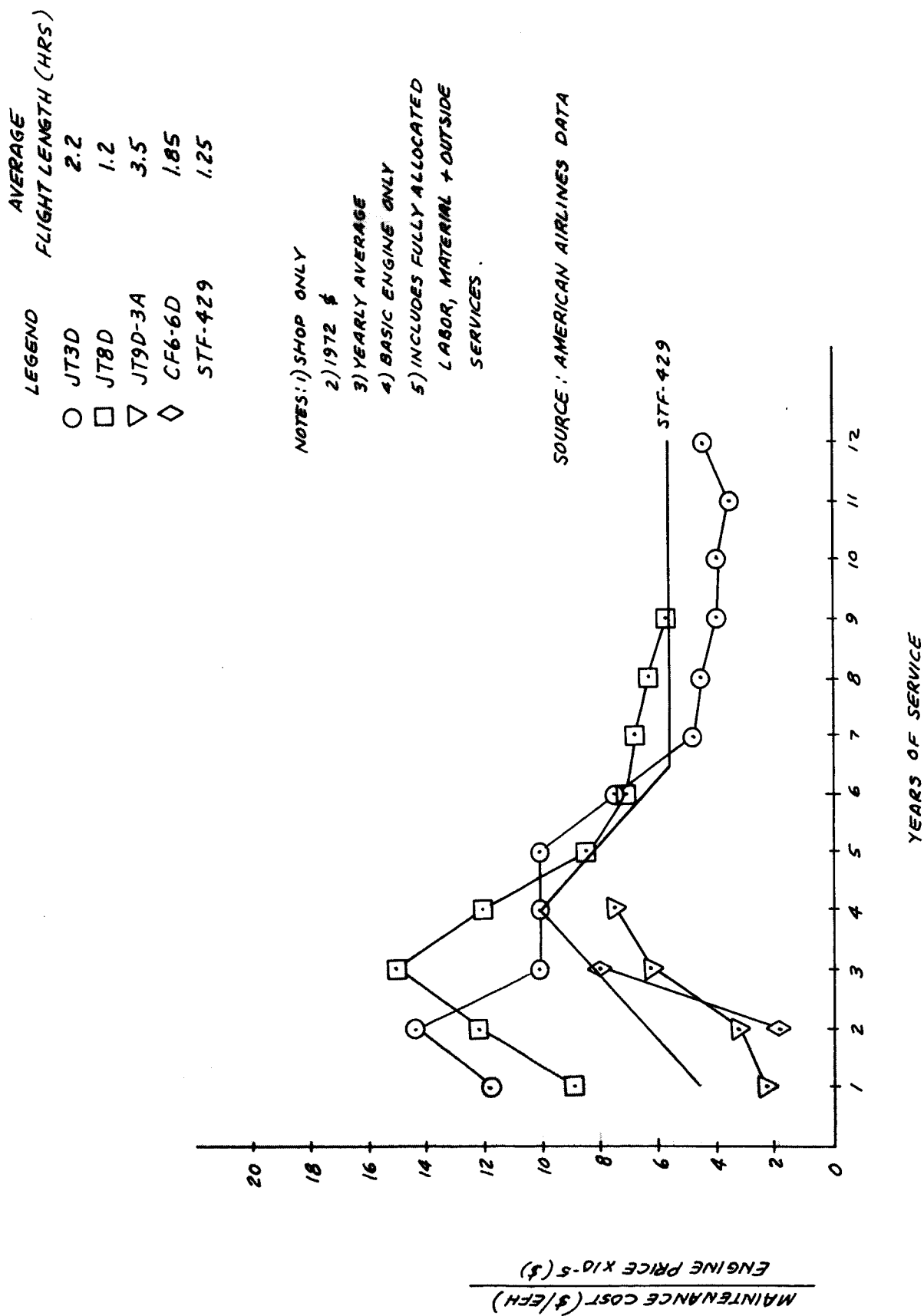


Figure IV-38 Comparison of Total Estimated STF 429 Maintenance Cost Per Engine Flight Hour, Normalized for Engine Price, With JT3D, JT8D, and JT9D Experience

V. TASK III. Preparation and Analysis of the Base Line Design by the ATA 1967 Method for Direct Operating Costs and the Lockheed Method for Indirect Operation Costs.

A. Introduction

In this section the cost to maintain the advanced aircraft propulsion system identified in Section IV will be determined by means of the 1967 ATA method for determining direct operating costs and by the Lockheed method for determining indirect operating costs as appropriate. The differences in the maintenance cost of the propulsion system determined by detailed analysis in Section IV and those determined herein by the more widely used ATA methods will be examined along with the sources of the differences observed. Lastly, a new method of forecasting propulsion system maintenance costs is presented for both mature power plants and for the early, first five year period in service. The limitations applicable to the suggested techniques are discussed.

It is the purpose of the section to show the inadequacies of the ATA methodology in accurately forecasting the maintenance cost impact of advanced propulsion systems and concurrently to define a more realistic and practical method for forecasting not only the maintenance cost impact but where opportunities exist for reducing the overall operating costs of future propulsion systems. These items will be discussed in Section VI. It is essential that the reader have an understanding of how the ATA equation is corrected by the various airframe and engine manufacturers; and how this updating process in of itself, misdirects the results of analysis when applied to advanced technology propulsion systems and, although not the subject of this study the aircraft operating costs as a whole. In general, it is the opinion of the study authors that very little economic insight can be obtained on advanced subsonic aircraft types including these propulsion systems using the ATA methodology, and that the fault lies with these economic assessment

methods which fail to reflect the true value of the advancements. Equally true is that these methods cannot define where real economic benefits could be achieved from advanced technology except in a gross sense. The current ATA method suggests with respect to engines that reduced engine thrust, lighter engine weight, lower S.F.C., fewer engines per aircraft and lower engine price are the major important propulsion system variables in aircraft operating cost. To be sure, each of these factors are important to the overall operating cost of an aircraft. However, not all of these variables are necessarily relevant to engine maintenance cost as will be discussed herein and as shown in Section IV.

V.B. Update of ATA-1967 D.O.C. Method Coefficients and Airplane Related I.O.C.

The 1967 ATA formula for calculating direct operating costs is periodically updated to reflect current year prices and airline operating experience. It is maintained to allow estimation of relative direct operating cost of competitive airplanes on a consistent basis. While the insurance rate and depreciation schedule are selected for consistency in aircraft comparison and may not reflect any particular airline practice, they do reflect average airline practice. The formula is used to project mature level maintenance costs. The mission profile and distribution of accounts of the basic 1967 ATA formula have been retained.

Comparison of reported direct operating costs with calculated 1967 ATA formula costs has shown increasing discrepancies in level and distribution by account. The 1967 ATA formula was based largely on 707/DC-8 experience prior to 1967. Since then much additional data have been obtained including the effect of the learning curve and product improvement on maintenance cost.

The Boeing update to the ATA operating cost coefficients is based largely on reported costs. Reported maintenance costs are adjusted to mature level and outside maintenance is adjusted and added to the airline maintenance. Maintenance costs for the wide body airplanes are based on ATA Spec 100 system analyses compared with the standard body airplanes.

Crew pay is based on a typical crew contract thus better reflects the effect of airplane size than did the 1967 ATA formula.

The depreciation period was lengthened and a residual value added to reflect average airline practice.

Utilization was reduced by five percent from the 1967 ATA formula to more nearly represent average experience.

Fuel price has been adjusted to reflect recent increases.

Table V-1 Summaries the factors used in calculating direct operating cost
Table V--2-- shows the coefficients used for the study for both D.O.C.
and airplane related I.O.C.s

DIRECT OPERATING COST LEVEL BASIS (DOMESTIC OPERATION)

MISSION PROFILE	<p>1967 ATA RULES</p> <ul style="list-style-type: none"> • 6 MINUTE AIR MANEUVER • 200 NMI ALTERNATE • 17 NMI - 2% DISTANCE FACTOR • 14 MINUTE TAXI TIME
UTILIZATION	1967 ATA REDUCED BY FIVE PERCENT (3650 BLOCK HOURS/PER YEAR FOR 1000 NMI AVERAGE TRIP)
CREW PAY	600 HOURS ANNUAL UTILIZATION, 1972 AVERAGE PAY FACTORS
FUEL PRICE	18¢/GALLON PLUS 2% FOR NON-REVENUE FLYING
MAINTENANCE	<ul style="list-style-type: none"> • RECOGNIZES FLIGHT HOUR AND CYCLE COSTS FOR MATURE LEVEL USING GENERALIZED PARAMETERS FOR PRELIMINARY DESIGNS AND DETAILED ANALYSIS FOR OPERATING AIRPLANES (2% FOR NON-REVENUE FLYING INCLUDED) • LABOR RATE = \$6.50/HOUR, BURDEN = DIRECT
DEPRECIATION	14 YEARS TO 10%
INSURANCE	1% FLYAWAY COST YEAR
SPARES	AIRFRAME: 6% OF COST ENGINE: 30% OF COST
PRICE BASIS	1972 DOLLARS

TABLE V-1

TABLE V - 2 FORMULA FOR OPERATING COST

(DOMESTIC OPERATION)

1974 ATA Formula in 1972 Dollars

ITEM	ASSUMPTIONS	FORMULA
● DIRECT OPERATING COST		
UTILIZATION	1967 ATA REDUCED BY FIVE PERCENT	$U = \frac{4275}{1 + \frac{BT}{.3}} + 475$
DEPRECIATION	14 YEARS TO 10%	
INSURANCE	1% FLYAWAY COST PER YEAR	
SPARES	• AIRFRAME 6% OF COST • ENGINE 30% OF COST	
CREW PAY	• 600 HOURS ANNUAL UTILIZATION • 1972 AVERAGE PAY FACTOR • 3-MAN CREW	$17.605 (V_{CR} \times \frac{TOGW}{10^3})^{.3} + 41.81$
FUEL	\$.18/GALLON	
AIRFRAME MAINTENANCE	• MATERIAL \$/FLIGHT CYCLE -----	$2.411 C_a/10^6 + 2.103$
	• DIRECT LABOR/FLIGHT CYCLE -----	$9.378 \log_{10} \left(\frac{W_a}{1000} \right) - 14.848$
	• MATERIAL \$/FLIGHT HOUR -----	$2.015 C_e/10^6 - .998$
	• DIRECT LABOR/FLIGHT HOUR -----	$5.700 \log_{10} \left(\frac{W_a}{1000} \right) - 7.651$
PROPULSION SYSTEM MAINTENANCE	• MATERIAL \$/FLIGHT CYCLE -----	$6.680 (C_e/10^6) N_e$
	• DIRECT LABOR/FLIGHT CYCLE -----	$(.00188 T/10^3 + .186) N_e$
	• MATERIAL \$/FLIGHT HOUR -----	$18.357 (C_e/10^6) N_e$
	• DIRECT LABOR/FLIGHT HOUR -----	$(.00608 T/10^3 + .6264) N_e$
MAINTENANCE BURDEN	100% OF DIRECT MAINTENANCE	
LABOR RATE	\$6.50 PER HOUR	
NO REVENUE FACTOR	1.02 ON FUEL AND MAINTENANCE	
● AIRPLANE RELATED INDIRECT OPERATING COSTS		
CABIN ATTENDANT EXPENSE	\$ PER BLOCK HOUR	$\frac{Seals}{27} \times 18.00 (\text{Std Body})$ $\left(\frac{Seals}{27} + 1 \right) \times 18.00 (\text{Wide Body})$
AIRCRAFT SERVICING	• \$ PER CYCLE	
	• FUELING AND CLEANING -----	$.70 \times \text{Max Lnd Wt}/1000$
	• LANDING FEE -----	$.385 \times \text{Max Lnd Wt}/1000$
	• AIRCRAFT CONTROL -----	\$43
GROUND EQUIPMENT AND FACILITIES	• \$ PER CYCLE	
	• MAINTENANCE AND BURDEN -----	$.39 \times \text{Max Lnd Wt}/1000$
	• DEPRECIATION AND AMORTIZATION -----	$.418 \times \text{Max Lnd Wt}/1000$
GENERAL AND ADMINISTRATIVE	\$ PER TRIP	$.06 (\text{Cash DOC} + \text{Airc. Ref. IOC} - G \& A)$

ABBREVIATIONS

TOGW = MAXIMUM TAKEOFF GROSS WEIGHT - POUNDS
 C_a = AIRFRAME PRICE - DOLLARS
 C_e = ENGINE PRICE - DOLLARS
 N_e = NUMBER OF ENGINES
 T = SEA LEVEL STATIC THRUST/ENGINE - POUNDS

W_a = AIRFRAME WEIGHT
 FH = FLIGHT HOURS
 MH = MANHOURS
 BT = BLOCK TIME - HOURS
 V_c = SPEED FACTOR = $715 (\text{MACH}) - 75 (\text{MACH})^4$

C. Analysis of Base Line Designs by ATA 1967 Method and Lockheed Method for Direct and Indirect Operating Costs

1. Direct Operating Costs

The fundamental variables needed to estimate the base line aircraft's direct operating costs by the ATA method are set forth below:

Block Time (BT)	=	1.5 Hours
Airframe Weight (Wa)	=	120,340 Lbs.
Airframe Price (Ca)	=	\$11,600,000
Engine Price (Ce)	=	\$ 1,050,000
Number of Engines (We)	=	3
Sea Level Static Thrust/Engine - Pounds (T)	=	22,000
Cruise Speed (Mach)	=	.84
Fuel Price	=	18¢/Gal.
Block Fuel	=	14,800 Lbs.
Flight Hours (FH)	=	1.25

While the average 1972 airline labor rate was \$6.50 per hour, American's labor rate was \$7.00 and this rate will be used for consistency between the data presented. The following represents the calculated direct operating cost for the aircraft based on the ATA formula shown previously:

TABLE V 3

Direct Operating Cost for D-179C/STF429
(By ATA Method)

	<u>\$/Hr.</u>
Depreciation	\$ 392.30
Insurance	54.91
Crew Pay	233.17
Airframe Maintenance Direct	101.99
Airframe Maintenance Burden	101.99
Engine Maintenance Direct	92.16
Engine Maintenance Burden	92.16
Fuel	318.09
Non-Revenue Factor - 2% of Mtce. & Fuel	14.13
Total	<u>\$1,400.89</u>

a. "Engine" Maintenance Cost.

The engine maintenance cost are \$24.88 for material, \$5.84 for labor per engine flight hour for a total of \$30.72 per engine flight hour or \$92.16 per aircraft flight hour. Comparing the estimated maintenance cost with those developed in section IV for the mature STF429 as shown below leads to the necessity of reviewing the overall reasons for the difference.

TABLE V-4 Comparison of
STF429 Engine Maintenance Cost - Mature Level

	<u>ATA Method</u>	<u>Study Method</u>	<u>Mature Engine Difference</u>
Direct Labor \$/EFH	5.84	7.80	+ 34%
Material \$/EFH	24.88	41.36	+ 66%
O.S.S. \$/EFH	--	3.46	--
Burden \$/EFH	30.72	16.13	- 48%
Total \$/EFH	61.44	68.75	+ 12%

This newer (updated coefficients) ATA equation differs in total level of maintenance cost by only 12% which is not too significantly different from the more detailed estimate. However, the ATA method understates both labor and material costs while overstating burden. The revised coefficients on the ATA equation presented represent regression matching of 1973 cost experience (stated in 1972 dollars) as reported in CAB accounts and do not reflect the normal life cycle costs experience of other engines including the new high bypass ratio engines. The labor/material cost ratio for the new high bypass engines is quite different from the older more mature low bypass ratio engines due to modular design. In order to obtain a regression fit, burden was apparently applied to both labor and material rather than labor alone as had been previous practice. In actual fact, the labor required to maintain the mature high bypass ratio engines is estimated to be quite similar to older

engines while the material cost reflects the higher cost of the higher performance and more complex engines. The physical size of the core engines of the JT9D/CF6 class engines compared with the JT3D/JT8D differs only slightly. The labor required therefore will remain relatively the same, influenced only by the rate at which repairs are required and the actual complexity of the engine, as described in section IV, and does not relate to the thrust level of the engine at all.

If the ATA engine maintenance costs are compared to the estimated introductory engine costs as shown below, the divergence is even greater. The ATA costing method only attempts to project the mature engine maintenance costs and does not recognize the higher maintenance costs normally encountered during the introduction into service of new propulsion systems caused by early unreliability.

TABLE V-5 Comparison
STF429 Maintenance Cost - Initial Operation

	<u>ATA</u>	<u>Introduction Into Service Study Method</u>	<u>Difference</u>
Direct Labor \$/EFH	\$ 5.84	\$ 12.48	+114%
Material \$/EFH	24.88	68.82	+177%
O.S.S. \$/EFH	--	5.60	--
Burden \$EFH	30.72	25.84	16%
Total \$/EFH	61.44	112.74	85%

In terms of propulsion system maintenance cost the analysis developed in section IV of this report on a total basis produces mature burdened maintenance costs only slightly higher than the revised ATA equation shown here, (12%) The additional detail provided by the more in-depth analysis has produced more realistic estimates of the propulsion system maintenance elements and the impact of early propulsion system maintenance cost elements and the impact of early propulsion system unreliability on maintenance costs.

2. Depreciation

No particular difference would be noted comparing the depreciation of investment in aircraft and engines or total spares for this study versus those shown by the ATA method. It should be recalled however, that for the propulsion system, spares are provided by both engine and airframe manufacturer. Further the ATA estimate of 30% of engine price as the cost for spares is only generally true as the real investment in spares varies during the life of the propulsion system in service as described in paragraph IV.C.2.b.. The investment in propulsion system spares is estimated to be 40% of the basic engine price per aircraft. This factor should be used when studying propulsion system alternatives.

3. Fuel Costs

No change in the operating cost for fuel is suggested other than the price per gallon will not stay fixed and is currently varying very rapidly. For this study the price of fuel was fixed at 18¢ per gallon which is already, as of this printing, out of date.

Indirect Operating Costs

The indirect area of aircraft operating costs is impacted only in facilities and tooling costs for the propulsion system. Based on the Lockheed method, the base line aircraft indirect cost for ground equipment and Facilities - Maintenance and Burden are estimated to be \$82.49 per aircraft cycle and the Depreciation and Amortization of these facilities \$88.41 per aircraft cycle. These costs reflect all ground facilities and equipment rather than just maintenance facilities alone. The estimated hourly cost for the ground facilities and equipment would be \$136.71 per flight hour. From section IV, the depreciation of propulsion maintenance and tooling has been estimated at \$1.42 per flight hour. Therefore, the engine does not impact indirect operating costs to any significant extent

and can be ignored except where very special facilities beyond those currently required for engine maintenance would be required.

D. Recommendations for New Method of Forecasting Propulsion System Maintenance Costs

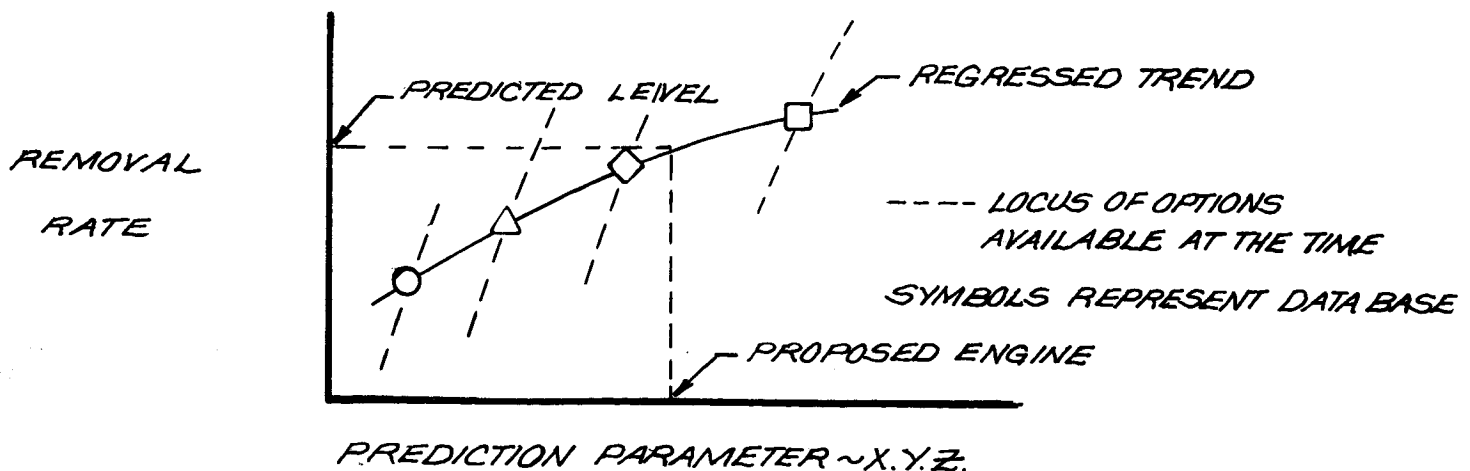
1. Introduction

One of the primary shortcomings of the current method of estimating aircraft operating economics (1967 ATA) is the technique for predicting propulsion system maintenance costs. This is quite understandable in light of the data base available at the time of inception. Two new methods (a long form, more detailed method, and a short form, less complex method) are proposed for use in predicting maintenance costs of advanced propulsion systems.

It should be remembered that any prediction technique based on a regression analysis has shortcomings. These shortcomings are much the same as those found in the prediction of the weather, it's fine as long as someone doesn't do something about it. Fortunately for meteorologists the weather is not tampered with whereas gas turbine design can, and probably will be, altered by maintenance constraints and predictions. This makes forecasting maintenance costs difficult if one envisions the ultimate purpose of the prediction as an realistic estimate of the engine maintenance cost.

If, however, one uses the prediction method as a tool to estimate what will happen if past experience is not deviated from, then the proper perspective has been established. The sketch below may assist in clarifying the value and shortcomings of a regression.

HYPOTHETICAL REGRESSION



The sketch depicts a regression of removal rates based on the experience of four hypothetical engines. These engines represent different times and design circumstances and the dashed lines through each data point represent a possible set of alternatives that may have existed at that time.

The predicted removal rate for the new engine implies that it was designed with "typical" design philosophy. If this predicted level is for any reason unacceptable, an examination of those options available should be made. This examination would not involve the use of a regression, but a more refined, detail approach. The purpose of the prediction technique was to "raise a flag" to the designer and provide a preliminary level for economic analysis.

Recommended Methods

The Long form method for estimating maintenance costs of the basic engine was based on a module-by-module analysis of repair costs and removal rates. This method requires a detailed description of the engine's six major modules. This description includes pressures, temperatures, diameters, tip speeds, stages and prices and is outlined in Tables V-6 and V-7.

The complexity of the long form method precludes its use as a rough and quick estimator of basic engine maintenance cost levels. In order to satisfy the demand for such a tool, a second method and suggested 1967 ATA replacement, the short form method, was established. Table V-8 describes this method. The increased simplicity of this method is paid for in its decreased sensitivity.

The propulsion system line maintenance cost and installation shop maintenance costs are treated in a similar long and short form approach.

The combined short form for estimating total propulsion system maintenance - labor, material and O.S.S.-costs per flight hour are shown in Table V-9, compared to the ATA equation. This short form is recommended as a replacement for the Propulsion system cost equations in the ATA formulation.

BASIC ENGINE MAINTENANCE COST FORECASTING ~ LONG FORM METHOD

TABLE Y-6

MODULE	MTBR = MEAN TIME BETWEEN REPAIR ~ HOURS	MH/REPAIR = MAN HOURS PER REPAIR ~ HOURS	MMC/REPAIR = MATERIALS COST PER REPAIR ~ \$
FAN/LOW COMPRESSOR	7368 YLPC ~ .874	95 ZLPC + 33	.125 x MODULE PRICE
HIGH COMPRESSOR	7368 YHPC ~ .874	95 ZHPC + 33	.114 x MODULE PRICE
DIFFUSER	5000	175	.164 x MODULE PRICE
COMBUSTOR	-1.25 YCBS + 4500	250	.124 x MODULE PRICE
HIGH TURBINE	-530 YHPT + 5650	1.49 ZHPT .611	.238 x MODULE PRICE
LOW TURBINE	-530 YLPT + 5650	1.49 ZLPT .611	.089 x MODULE PRICE

WHERE:

$$Y_{LPC} = TFS \times (PTS/PT2) \times \frac{1}{\#STGS_{FAN} + \#STGS_{LPC}} \times U_{T_{FAN/LPC}} \times 10^{-6} ; Z_{LPC} = U_{T_{FAN}}^2 \times DIAMETER_{FAN} \times \#STGS_{FAN} + U_{T_{LPC}}^2 \times DIAMETER_{LPC} \times \#STGS_{LPC} \times 10^{-8}$$

$$Y_{HPC} = TTH \times (PTV/PT3) \times \frac{1}{\#STGS_{HPC}} \times U_{T_{HPC}} \times 10^{-6} ; Z_{HPC} = U_{T_{HPC}}^2 \times DIAMETER_{HPC} \times \#STGS_{HPC} \times 10^{-8}$$

$$Y_{CBS} = TFS - TTH$$

$$Y_{HPT} = \sqrt{TFS} \times PT6/PT6 \times U_{T_{HPT}} \times \#STGS_{HPT} \times 10^{-5} ; Z_{HPT} = \sqrt{TFS} \times DIAMETER_{HPT} \times \#STGS_{HPT}$$

$$Y_{LPT} = \sqrt{TTH} \times PT6/PT4 \times U_{T_{LPT}} \times \#STGS_{LPT} \times 10^{-5} ; Z_{LPT} = \sqrt{TTH} \times DIAMETER_{LPT} \times \#STGS_{LPT}$$

TEMPERATURES ~ °R, SEA LEVEL TAKEOFF, HOT DAY

TIP SPEEDS ~ FT/SEC., SEA LEVEL TAKEOFF, HOT DAY (USE 1ST STAGE EXCEPT (T_{FAN/LPC}; THE STAGE WEIGHTED AVERAGE)

PRESSURES ~ PSIA, SEA LEVEL TAKEOFF, HOT DAY

DIAMETER ~ INCHES: FAN ~ FAN BLADE TIP

HPT ~ 1ST STAGE BLADE TIP

LPC ~ 1ST STAGE BLADE TIP

LPT ~ MEAN LPT BLADE TIP

HPC ~ 1ST STAGE BLADE TIP

BASIC ENGINE MAINTENANCE COST FORECASTING - LONG FORM METHOD

TABLE V-7

RESULTS FROM TABLE I ARE USED TO PREDICT ENGINE MAINTENANCE COSTS:

$$\begin{aligned} \text{MAINTENANCE MATERIALS COST/FLIGHT HOUR} &= \sum_{6 \text{ MODULES}} (\text{MMC/REPAIR} \times 1/\text{MTBR}) \times 1.18 \times (\text{FLIGHT TIME})^{.28} \\ \text{MAINTENANCE LABOR COST/FLIGHT HOUR} &= \left\{ \sum_{6 \text{ MODULES}} (\text{MH/REPAIR} \times 1/\text{MTBR}) + .19 \right\} \times 1.065 (\text{FLIGHT TIME})^{.28} \\ &\quad \times \text{LABOR RATE} \end{aligned}$$

MEAN TIME BETWEEN REPAIR (TOTAL ENGINE) = .83 X CRITICAL MODULE MTBR

THESE COSTS ARE FOR:

- . BASIC ENGINE
- . SHOP ONLY
- . MATURE LEVEL

. TO INCLUDE OUTSIDE SERVICES, MULTIPLY MAINTENANCE MATERIALS + LABOR (FULLY BURDENED) BY 1.065

TO ESTIMATE MATURITY EFFECT USE THE FOLLOWING FACTORS ON MATURE LEVEL

FIRST FIVE YEAR AVERAGE

MTBR	2.2
MH/REPAIR FACTOR	.7
MMC/REPAIR FACTOR	.7

BASIC ENGINE MAINTENANCE COST FORECASTING ~ SHORT FORM METHOD

TABLE V-8

$$\text{MTBR} = .939 \times \text{FLIGHT TIME} \times e^{(-.00018 (\text{C.E.T.}) + 8.17)}$$

$$\text{MMC/FH} = .082 \times \text{ENGINE PRICE/MTBR}$$

$$\text{LABOR COST/FH} = 1400/\text{MTBR} \times \text{RATE}$$

WHERE C.E.T. = COMBUSTOR EXIT TEMPERATURE ~ °F, SEA LEVEL STATIC, HOT DAY, TAKEOFF

THE QUALIFICATIONS ON THIS METHOD ARE THE SAME AS THOSE IN TABLE II

TO INCLUDE OUTSIDE SERVICES, MULTIPLY MAINTENANCE MATERIALS + LABOR (FULLY BURDENED) BY 1.065

INSTALLATION DIRECT MAINTENANCE COSTS - LONG FORMULA

. Total Line Direct Labor (LL_T) - \$/EFH

a) 2 (Installation Line Labor) = LL_T

$$2 \left[LL_{71} + \frac{X}{1.15} (LL_{78} + LL_{80}) + LL_R \right] = \text{Labor Rate} = LL_T$$

X = Ratio of Labor Cost at Study Flight Length, Fig. V-1

Subscript numbers represent particular ATA systems and

"R" represents the remaining power plant ATA's excluding 72.

b) $LL_{71} = 1.30 \times ERR \times MH$

1.30 = Factor to Account for Cowl & Some QEC Repair

ERR = Engine Removal Rate Per 1000 Engine Flight Hours

$$= \frac{1064 (\text{Aver. Flight Length})^{-0.28}}{e^{(-0.00018 \text{ CET} + 8.17)}}$$

CET = Combustion Exit Temperature, °F

MH = Manhours for Engine Change

$$= 14.5 + 0.00344 (\text{Basic Engine Weight})$$

c) $LL_{78} = N \times 0.020$

N = Number of Thrust Reversers Per Engine

d) $LL_{80} = 0.006$

e) $LL_R = ERR \times 75$

. Total Line Material (LM_T) - Dollars/EFH

a) $LM_T = 0.0014 \times \text{Engine Price} \times ERR$

. Installation Shop Direct Labor (SL_{Inst1}) - \$/EFH

$$a) \left[SL_{71} + \frac{X}{1.15} (SL_{78} + SL_{80}) + SL_R \right] = \text{Labor Rate} = SL_{Inst1}$$

b) $SL_{71} = ERR \times 1.30 \times MH$

MH = Manhours for QEC Build-up & Tear-down

$$= 0.0474 (\text{Basic Engine Weight})$$

c) $SL_{78} = N \times 0.04$

d) $SL_{80} = 0.014$

e) $SL_R = ERR \times 75$

. Installation Shop Material (SM_{Inst1}) - Dollar/EFH

$$a) SM_{71} + \frac{YA}{1.19} (SM_{78} + SM_{80}) + SM_R = SM_{Inst1}$$

Y = Ratio of Material Costs at Study Flight Length, Fig. V-2

A = Inflation Rate Using 1972 as Base Year

* Note = The engine removal rate from the basic engine long form method may be used to improve accuracy.

- b) $SM_{71} = 0.0015 \times \text{Engine Price} \times \text{ERR}$
- c) $SM_{78} = N \times 0.30$
- d) $SM_{80} = 0.15$
- e) $SM_R = 0.0007 \times \text{Engine Price} \times \text{ERR}$

INSTALLATION DIRECT MAINTENANCE COSTS - SHORT FORM

. Total Line Direct Material (LM_T) - Dollars/EFH

a) $LM_T = 0.0014 (\text{Engine Price}) \text{ ERR}$

. Installation Shop Direct Material (SM_{Instl}) - Dollars/EFH

a) $SM_{Instl} = 0.0039 (\text{Engine Price}) \text{ ERR}$

. Total Line Direct Labor (LL_T) - \$ /EFH

a) $LL_T = \left[\left[187 + 0.0089 (\text{Eng. Wt}) \right] \text{ ERR} + 0.035N + 0.011 \right] \text{ Labor Rate}$

. Installation Shop Direct Labor (SL_{Instl}) - MH/EFH

a) $SL_{Instl} = \left[\left[75 + 0.0616 (\text{Eng. Weight}) \right] \text{ ERR} + 0.035N + 0.012 \right] \text{ Labor Rate}$

N = Number of Thrust Reversers per Engine

ENGINE - LABOR

ALL MODELS

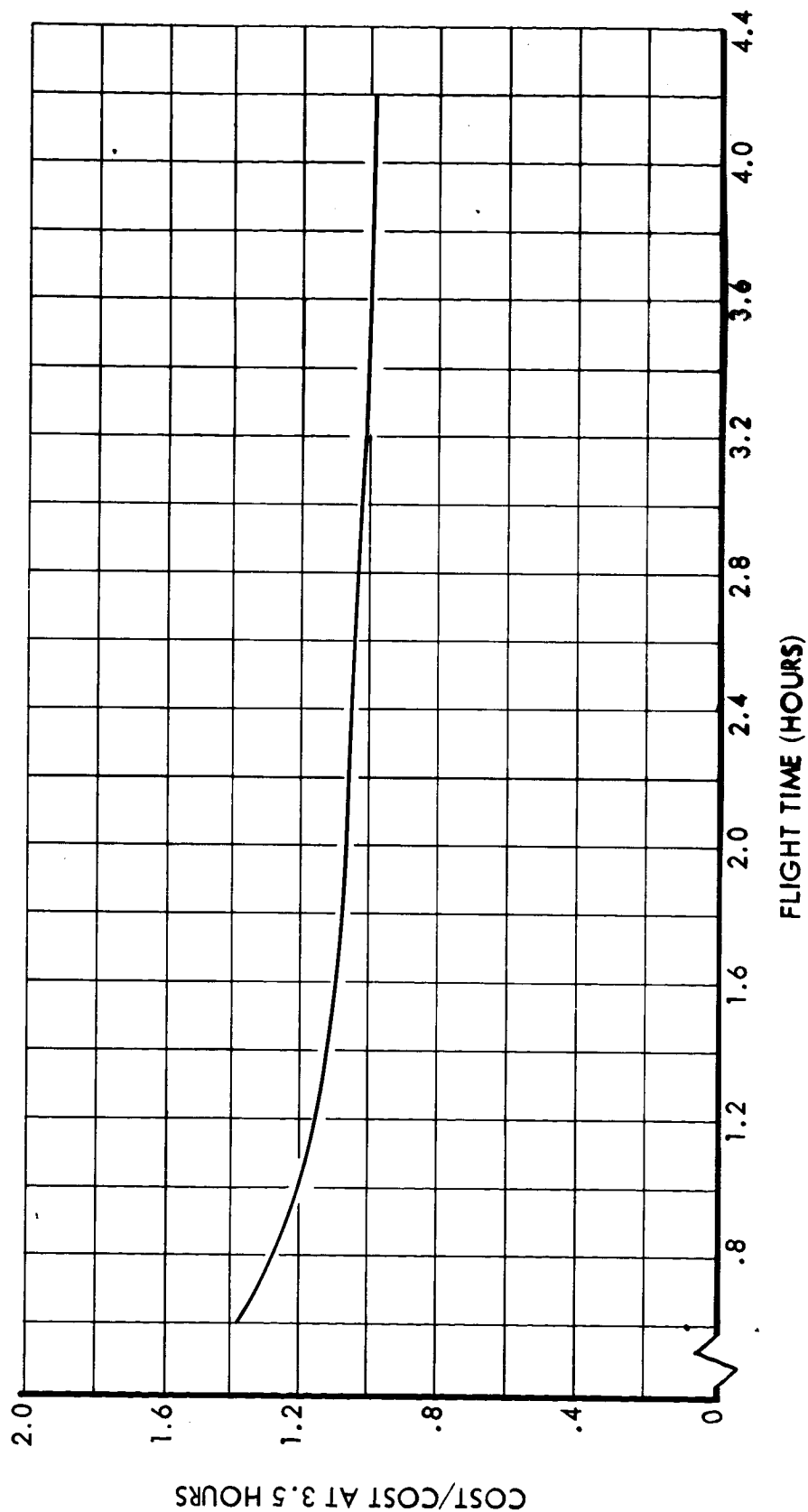


FIGURE V-1

4-3-74

ENGINE - MATERIAL

ALL MODELS

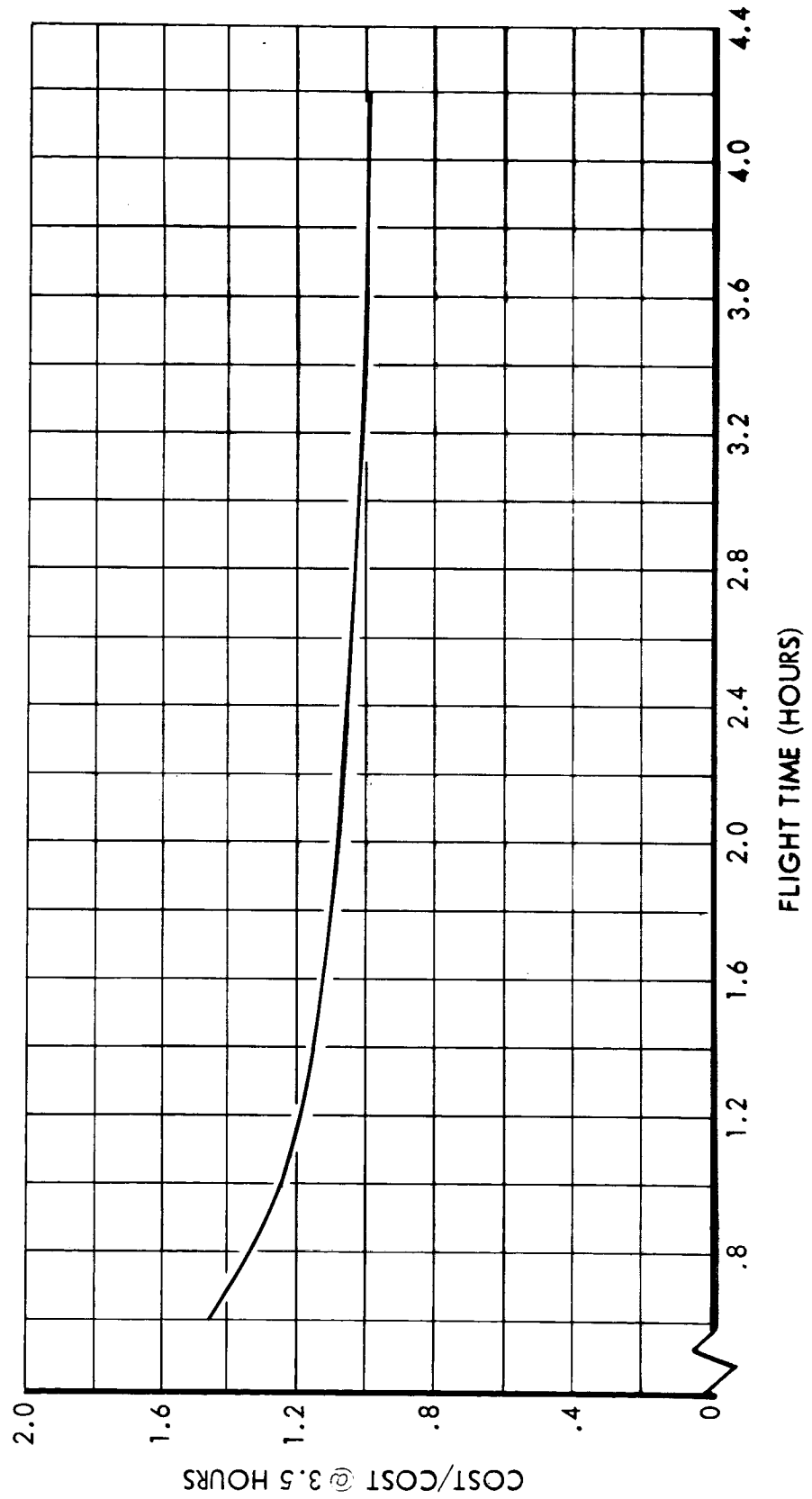


FIGURE V-2

1-574

**PROPULSION SYSTEM
DIRECT MAINTENANCE COST
JT9D/CF6 TYPE ENGINES AND ON**

	1974 ATA (1972 DOLLARS)	REVISED
MATERIAL	$6.680 (C_e / 10^6) N_e = \$/FC$ $18.357 (C_e / 10^6) N_e = \$/FH$	$[0.0873 (C_e) ERR] N_e = \$/FH$
DIRECT LABOR	$(0.00188T/10^3 + 0.186) N_e \times LR = \$/FC$ $(0.00608T/10^3 + 0.6264) N_e \times LR = \$/FH$	$[(1662 + 0.0705 W_e) ERR + 0.07N_e + 0.023] N_e \times LR = \$/FH$
OUTSIDE SERVICE		$0.065 N_e \times ERR [0.082 (C_e)$ $+ 1400 \text{ (OUTSIDE SERVICES LR)}] = \$/FH$

$$ERR = \text{ENGINE REMOVALS} = \left(\frac{1064 (\text{AVER. FLIGHT LENGTH})^{-0.28}}{2 (-0.00018 \text{ CET} + 8.17)} \right) \text{ PER 1000 EH}$$

VI. Task IV - Parametric Analysis of The Economic Effects of Major Propulsion System Design Features

A. Introduction

In the course of this study, historical propulsion system maintenance costs were examined for three major aircraft propulsion systems in an effort to determine trends of operating cost with technology. The knowledge of the distribution and level of the propulsion system maintenance effort expended on the various propulsion systems provides insight as to the technological areas where potential economic payoffs may be obtained with expenditure of advanced research effort on technology. This section of the report is directed at reviewing the general results and conclusions drawn from the earlier portions of this study. Included is a review of the recommended new methods of forecasting propulsion system maintenance costs and its general applicability. Lastly the economic impact of major propulsion system design features is reviewed to indicate where propulsion system operating costs could be reduced.

B. Impact of Propulsion System Maintenance Cost on Overall Aircraft Operating Cost

Propulsion systems impact operating costs in three major and one minor area:

- Depreciation of Investment (Direct Operating Cost)
 - Fuel (Direct Operating Cost)
 - Maintenance (Direct Operating Cost)
 - Facilities and Tooling (Indirect Operating Cost)
- Depreciation of investment includes the cost of the installed and spare propulsion systems and is a function of propulsion system price, system reliability, route structure and maintenance program.

- Fuel costs are based on engine performance as installed, the degree with which the maintenance program retains the performance of the engines and the price of fuel.
- The maintenance cost of a propulsion system is a function of the engine's reliability, the route structure on which it is used - average flight time, - the price of the engine or the major repair and life limited parts within the engine; and the complexity of the engine's installation. Higher turbine temperature engines historically result in higher prices and higher maintenance costs due to the higher cost of the parts which need to be replaced. Higher turbine temperature engines impact engine reliability early and therefore indirectly require higher investment in initial spares support. This, however, need not be so if properly addressed in the design and development process.
- Facility and tooling costs for the propulsion system represent a small and almost insignificant impact compared with the aircraft related facility and tooling cost.

General Observations From Task I and II

- Military Engine Experience:

Previous military experience does not appear to offer sufficient long term maintenance cost or reliability benefits to insist on a core engine developed by the military as a precondition to embarking on a commercial engine program. Two of the engines analyzed had and two did not have previous military experience. The utilization rate, hours per year, for commercial engines is in the area of 5 to 10 times higher than military usage. This experience accumulation rate suggests that at least military experience produces a benefit during the first year of commercial service. The military demand for lighter engines is counter productive to long life and ease of repair needed in commercial engines. No strong support is available to uphold the benefits of prior military experience in the maintenance cost and reliability data analyzed.

- Engine Thrust Level Impact on Maintenance:

The thrust level of the engines studied varied widely, however, no trend in labor cost with increasing or decreasing thrust level of engines was apparent. All of the engines tend to have core components that are very close in physical dimensions. The bulk of the labor is expended in repairing engine modules. A lesser portion of the labor cost is associated with the effort required to disassemble and reassemble the installed engine, and this cost has been greatly influenced by the way the propulsion system installation is designed. Labor costs per hour difference reflect the effort required to disassemble, repair and reassemble the power plant and the relative meantime between repair of the various components of the power plant.

- Life Cycle Costs

All engines studied cost considerably more to maintain during their introduction into service than when mature. Costs to repair engines early in service have been low but their average yield (time between repairs) has been poor, consequently the costs per hour are high. In general, the causes for these low yields have been dominated by turbine and combustor distress. Each new engine has had problems with turbine blade failures and combustor deterioration. Major modification programs have been undertaken on each engine to improve engine reliability. These programs have cost 10 to 30% of the engine purchase price. Several factors are involved. The development testing fails to uncover the deficiencies; the engine deteriorates in service causing turbine inlet temperatures higher than planned, and aircraft growth pushes thrust ratings higher than planned.

- Labor and Material in Engine Maintenance

The new modular designed high bypass ratio engines require relatively the same overall labor to repair as the older engines. The relationship between material and labor cost, however, has changed to reflect

higher purchase costs of replacement parts. The labor element, however, is sufficiently high to justify continued efforts to reduce the hours required for engine repair. Longer parts lives are equally required as the quantity of parts replaced per repair has not changed in mature engines. It is, therefore, quite probable that the criteria used to establish the designs of parts do accurately account for the reasons parts need to be replaced.

- Expendables:

Expendable parts - or parts which must be replaced as the result of a repair as required by the repairs manuals, represents 20 to 30 per cent of the material costs in each repair. Certainly this cost can be reduced although perhaps at some penalty in engine weight.

- Life Limited Parts:

Life limited parts normally require replacement three times during the life of an engine at roughly 4 to 6 years intervals. Life limited parts replacement costs which represent approximately 11 to 13% of an engine purchase price need to be expensed over total engine operating time to avoid high costs in particularly heavy replacement years. Continued improvement in minimizing life limited parts replacement costs is warranted with greatest attention being placed on uniform life limits within a module and ideally for all parts within the engine. Achievement of these goals will result in fewer engine removals for life limited parts replacement and lower costs for labor.

- Dispatch Reliability Costs:

The cost for maintenance of engines and their installation when looked at from a reliability standpoint provides additional perspective. As an example, the cost to maintain engine thrust reversers should be increased by the costs incurred from delays in revenue service caused by thrust reverser

unreliability. More emphasis should be placed in subsystem design and development process to insure minimum cost impact in these areas.

C. Assessment of General Applicability of The Recommended New Method of Forecasting Propulsion System Maintenance Costs

The maintenance cost prediction equations presented in Section V of this report have been developed for use with the modular engine designs and the newer high bypass ratio engines. The demands for noise and pollution control as well as low S.F.C. suggest the higher bypass ratio engine will be preferred if not required in the future. These equations were developed based on historical maintenance cost which allowed engine specific fuel consumption to deteriorate within the bounds of other controlling limits such as minimum thrust, maximum exhaust gas temperature and engine stall performance. The predicted costs should, therefore, be considered the costs consistent with allowing a certain limited amount of fuel consumption performance losses to occur. It would be expected that maintenance cost might rise in the future through efforts to arrest and control engine specific fuel consumption deterioration with time and that the equation will produce slightly understated costs if this occurs. The maintenance costs studied were for engines in a thrust size range for commercial and military subsonic transport aircraft. Caution should, therefore, be used in applying the cost methodology to turbojets or to small turbofans of less than 10,000 lbs. of thrust, as cost data was not available for representative commercial engines in these categories.

Further, none of the aircraft/engines costs studies, were for engines used on particularly short flights. (30 minutes or less). Reliable industry engine removal rate information was not available to project the impact of these shorter flight times. Nonetheless, American's experience does indicate that the shorter flights will adversely affect engine time between repairs and, thereby, cause a marked increase in propulsion system direct operating costs. There is no indication from Americans' experience that the cost per engine repair versus years of experience will significantly differ for engines in short flight duration service. The total engine removal rate, however, is higher due to low cycle fatigue effects as well as foreign object ingestion damage and greater exposure to erosion.

The major thrust of this study effort was to examine current engine operating cost with the objective of determining where technology could be employed to reduce the operating cost of future engines. Secondly, the economic methodologies developed should be useable to more realistically project the maintenance costs of future advanced technology propulsion systems. The measurement of success of this effort will be assessed in part by the rapidity with which the forecasting techniques suggested are made obsolete by technological changes brought about by increased understanding of where propulsion system maintenance cost can be reduced.

The maintenance costs projected by the suggested methods, both short as well as long forms, have been tested against current engine experience to the extent possible with the detailed data at hand. The results of this analysis as shown in Tables VI-1, 2 and 3 are considered to be acceptable and far more accurate than provided by the ATA method

METHODS COMPARISON

DIRECT PROPULSION SYSTEM MAINTENANCE COST
1972 DOLLARS/AIRPLANE FLIGHT HOUR

CAB FORM 41 DATA*	ATA FORMULA	STUDY FORMULA	
		LONG FORM	SHORT FORM
MODEL 707-120 @ 2.0 HR/FLIGHT			
MATERIALS	31.92	31.67	44.37
LABOR	21.99	20.43	21.55
OSS	-	3.25	4.31
TOTAL	53.91	55.35	70.23
MODEL 707-320 @ 3.0 HR/FLIGHT			
MATERIALS	30.28	28.37	39.61
LABOR	21.04	18.51	19.69
OSS	-	2.90	3.85
TOTAL	51.32	49.78	63.15
MODEL 727-100/200 @ 1.25 HR/FLIGHT			
MATERIALS	26.15	26.35	37.31
LABOR	17.26	15.51	16.39
OSS	-	2.84	3.68
TOTAL	43.41	44.70	57.38

* FLEET AVERAGE AFTER FIRST 5 YEARS OF SERVICE
FLEET AVERAGE LABOR RATE - \$6.50 DIRECT

TABLE VI-1

5/2/74

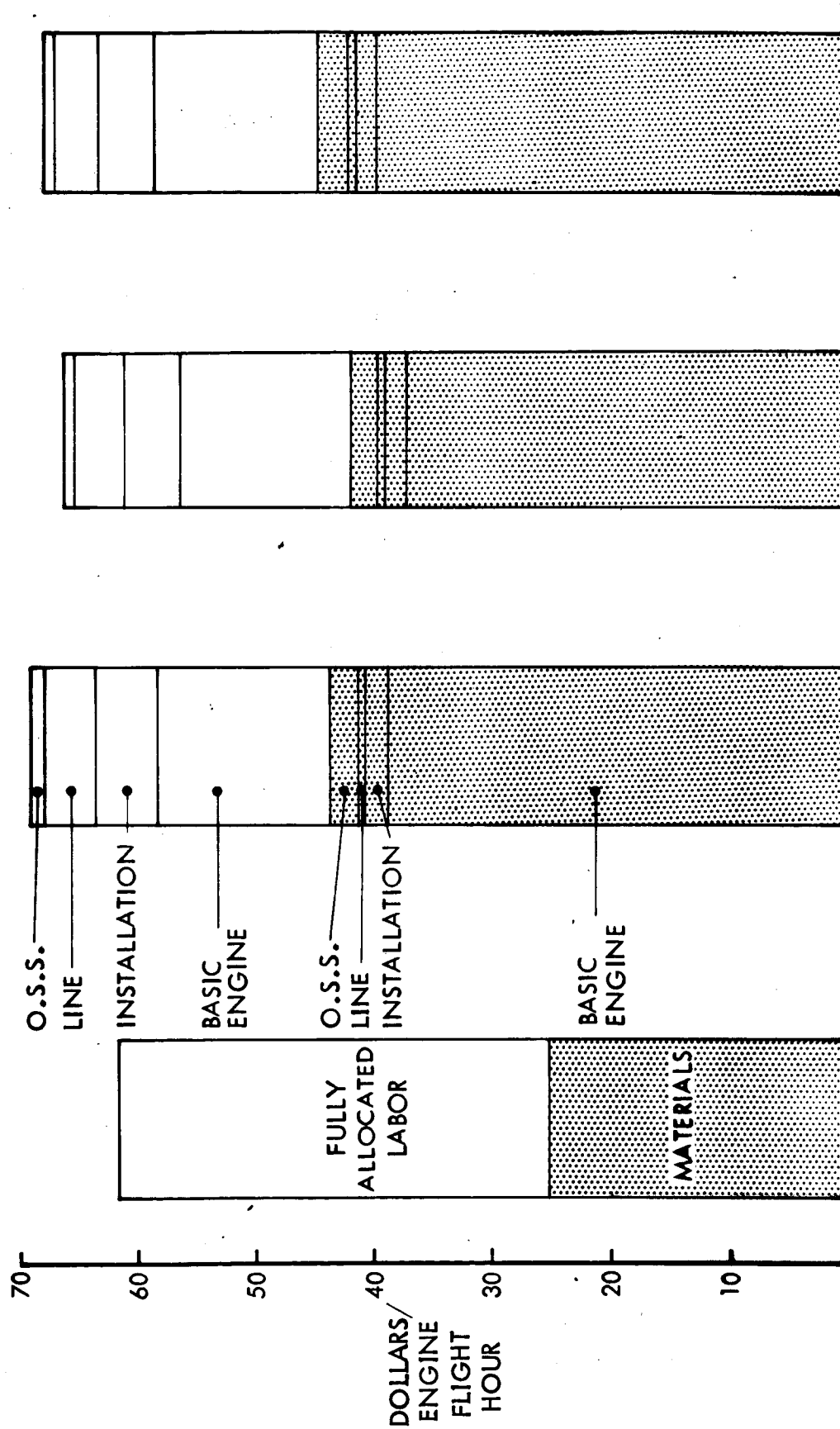
METHODS COMPARISON

PROPULSION SYSTEM MAINTENANCE COST
1972 DOLLARS/AIRPLANE-FLIGHT HOUR
MODEL 747-100 @ 3.5 HR/FLIGHT

	ATA FORMULA	STUDY FORMULA	
		LONG FORM	SHORT FORM
MATERIALS	72.38	100.12	99.85
LABOR	25.15	23.95	23.13
OUTSIDE SERVICE	-	8.77	8.42
BURDEN	97.53	49.50	47.80
TOTAL	195.06	182.34	179.20

MAINTENANCE COST METHODS COMPARISON

\$/ENGINE FLIGHT HOUR



SHORT FORM EQUATIONS

LONG FORM EQUATIONS

DETAILED COMPONENT ANALYSIS

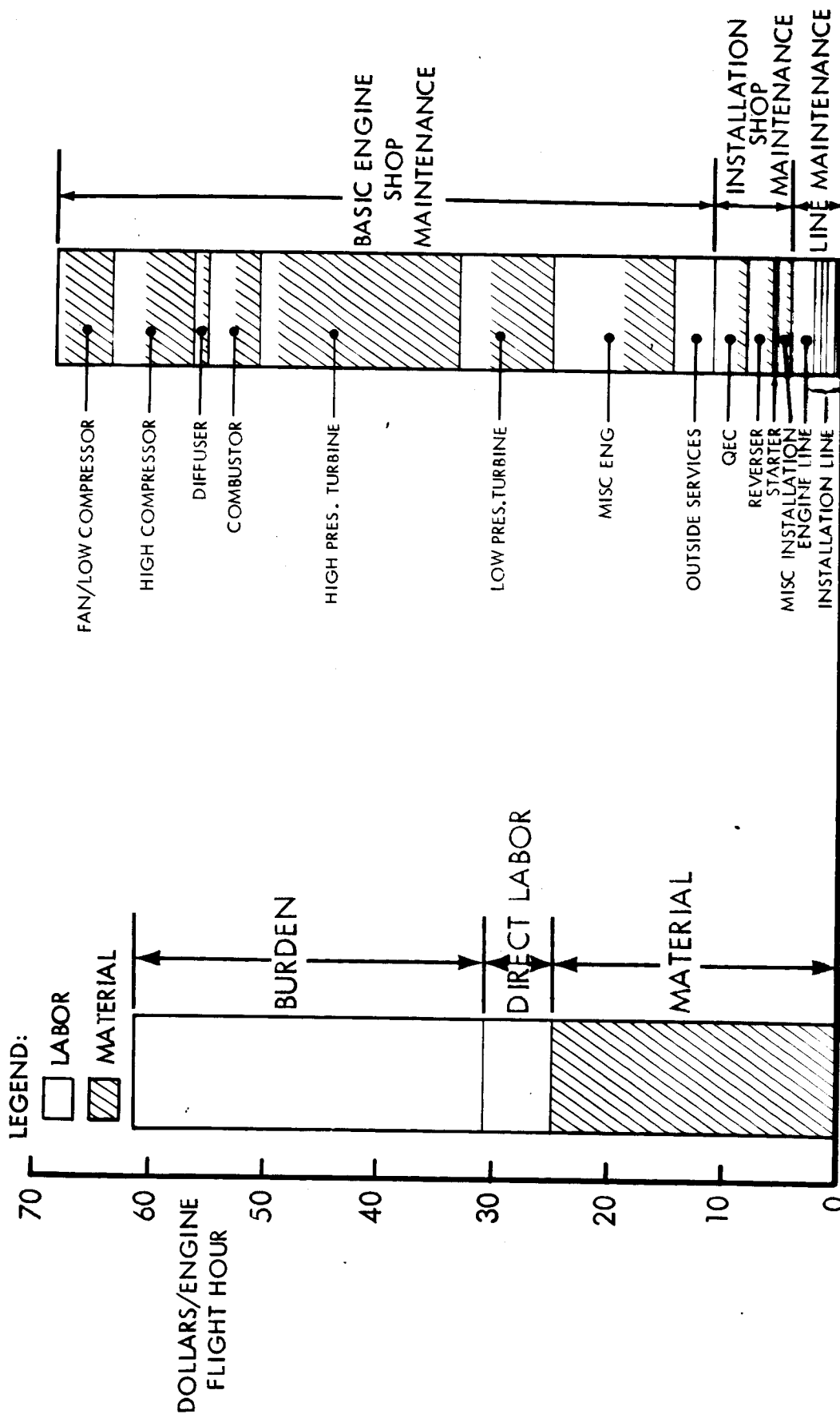
ATA FORMULA

TABLE VI-3

5/2/74

MAINTENANCE COST METHODS COMPARISON COST ELEMENT DEFINITION

D4-179C/STF 429



ATA
FORMULA

LONG FORM
EQUATIONS

5-28-74

The short form as noted in Table VI-1, overpredicts the material costs for the earlier engines. The constant in the material cost equation was selected for use with advanced engines. To use on the earlier engines, the constant should be multiplied by 0.7. The short form of the equation, Figure V-9, is suggested as a replacement to the ATA equations for advanced propulsion system maintenance costs. Manufacturers and NASA will find the long form more useful since it provides visibility, Table VI-4, and the inputs are available from match point performance computer programs and first flow path drawings. The input data as to component prices can be developed from inhouse experience by the manufacturers and could be requested on a proprietary basis by NASA and other government agencies from contractors in support of future studies. These data, however, would not be generally available or needed by the airline industry until firm business proposals for new engines were presented by the manufacturers.

D. Recommended Areas of Propulsion System Technology Which Should Be Pursued to Obtain Improved Operating Economics.

The following recommendations have been developed considering that the cost impact of new propulsion systems occurs in different areas as well as time-frames. The continuing cost for maintenance is directly impacted by initial cost and there are features which help reduce maintenance costs which will impact engine prices. The cost of early unreliability must be considered and programs developed to overcome these early costs.

Dispatch reliability costs need to be considered in the design process and first costs may be increased to provide improved reliability. Fuel costs represent the largest operating cost element, and the installation as well as maintenance of propulsion systems can effect these costs both directly and indirectly. Each of these areas will be treated in more detail in the following paragraphs.

1. Initial Purchase Costs

The purchase price of engines and their installations is a significant and growing part of aircraft price. The demands for improved pollution and noise characteristics, as well as performance from future engines, will increase this trend. The elements that go into establishing the purchase price of an engine are beyond the scope of this study but it is obvious that means must be found to reduce engine purchase prices to a minimum. The non-recurring or development cost for a propulsion system must, to a certain extent, be related to the effort required to meet the contractual performance objectives set for the engine and aircraft. Competitive pressures tend to ratchet manufacturers into promising more in the performance area than is comfortable or technologically well in hand. Future propulsion system competition will hopefully be based on total economics with all of its dimensions. Certainly the area of "design to cost" is supported.

a. The Value of Design Alternatives

A method that appears to have merit for evaluating the economic impact of design alternatives or improvements is to evaluate the increased earnings or decreased operating cost over the life of the airplane. This method assesses the cash flow difference caused by the alternatives, such as fuel saving, maintenance savings, differences in crew costs, etc. and equates those savings to a differential investment. For example in Figure VI-1, a 10% specific fuel consumption improvement would provide an airframe, with the same revenue producing capability (seat miles/trip), that used less fuel and had a lower weight. This results in a savings in fuel cost, crew pay, landing fee and airframe maintenance (assuming, as the ATA formula does, that airframe maintenance is a function of airframe weight). This cash flow

savings in a 3% annual inflation environment would be equivalent to an initial investment per airplane (price increase) of \$700,000 and 10% after tax return on that investment over the 14 years of service.

The three sets of curves, Figures VI-1, 2 and 3 show the relative value of single changes in SFC, maintenance, and engine weight and the effects of different inflation rates and fuel price. For the comparison it has been assumed that the revenue capability (seat mile/trip) remains constant and that the airplane and engines are resized in accordance with the respective improvement such that the improved airplane and engines are the smallest that meet the requirements.

b. Power Plant Installation

The cost of power plant installation has not received the scrutiny it deserves as this cost element has been basically hidden from airline view in the total cost of the aircraft. Because this element represents a high cost area, avenues to reduce the cost are obviously warranted. The objective of using the propulsion system in more than one aircraft type is a possible means to reduce the cost. Proprietary rights in the installation design make such wider use less likely unless the design is owned by the engine manufacturer. A second opportunity is to reduce to a minimum those parts of the engine installation which make up the installation buildup unit or QEC. This has double leverage in that it

VALUE OF DESIGN IMPROVEMENTS

(D4-179C/STF 429)

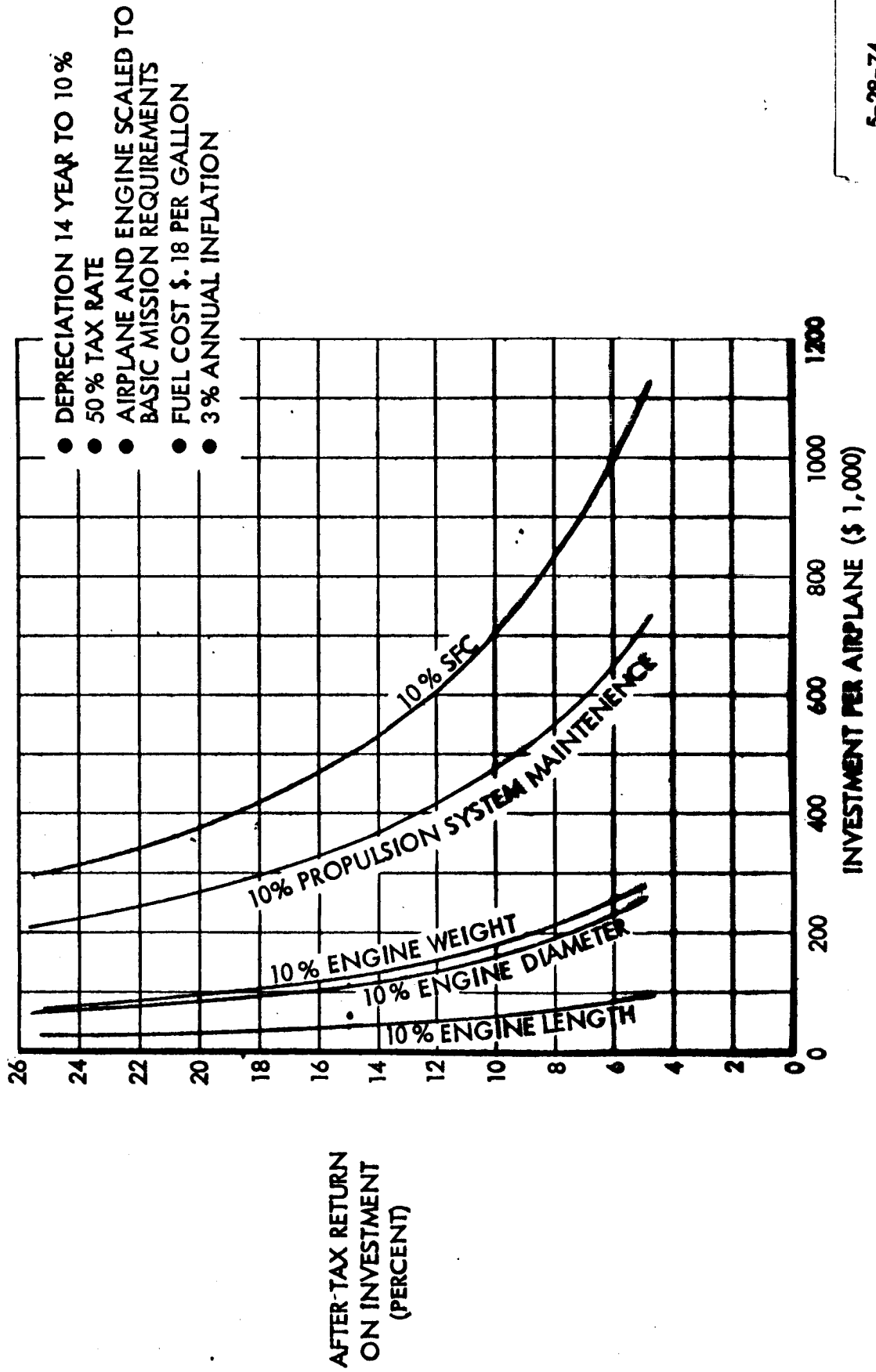


FIGURE VI-1

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VALUE OF 10% SFC IMPROVEMENT

EFFECT OF FUEL PRICE

(D4-179C/STF 429)

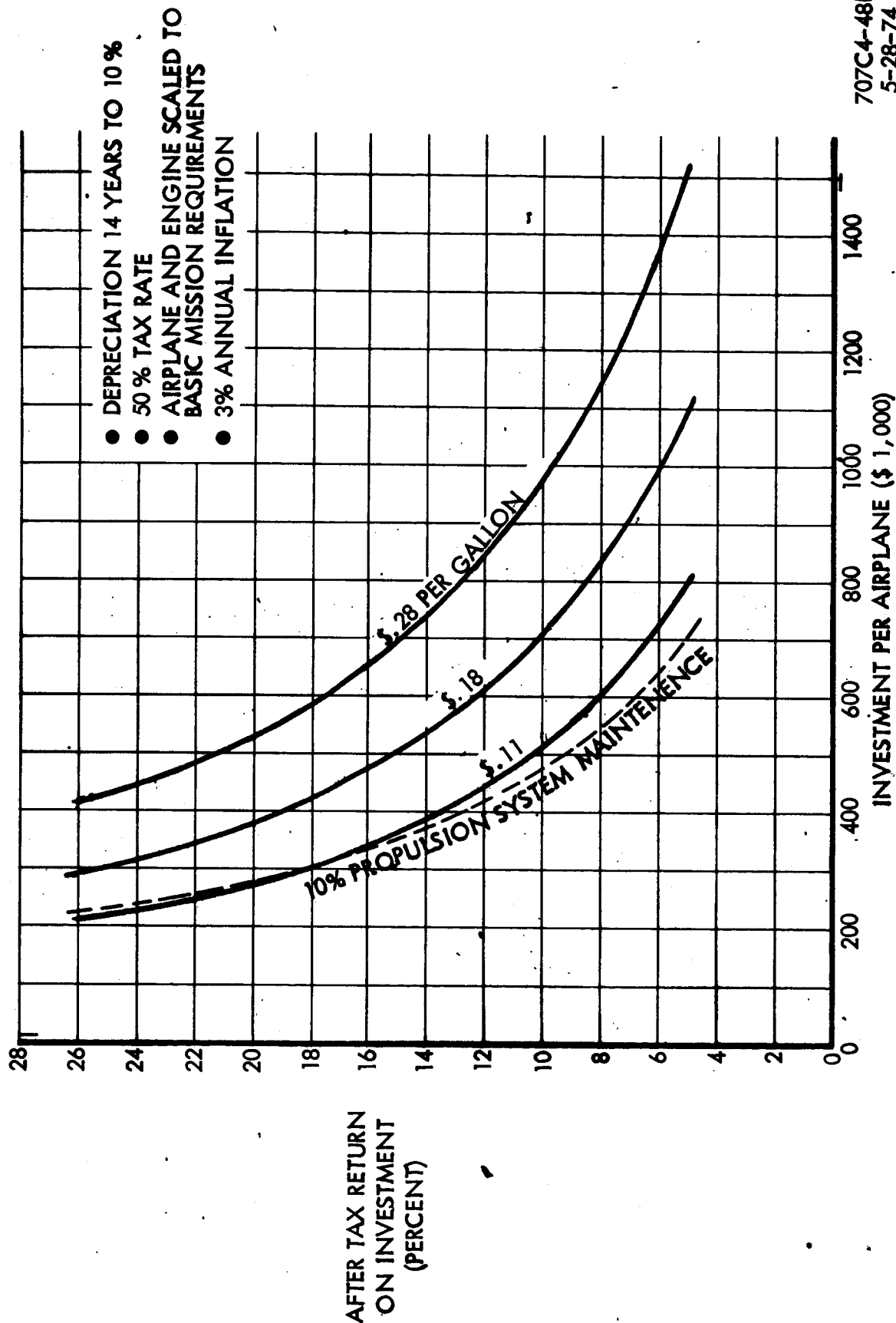


FIGURE VI-2

707C4-48R1(A)

VALUE OF 10% SFC IMPROVEMENT

EFFECT OF INFLATION RATE

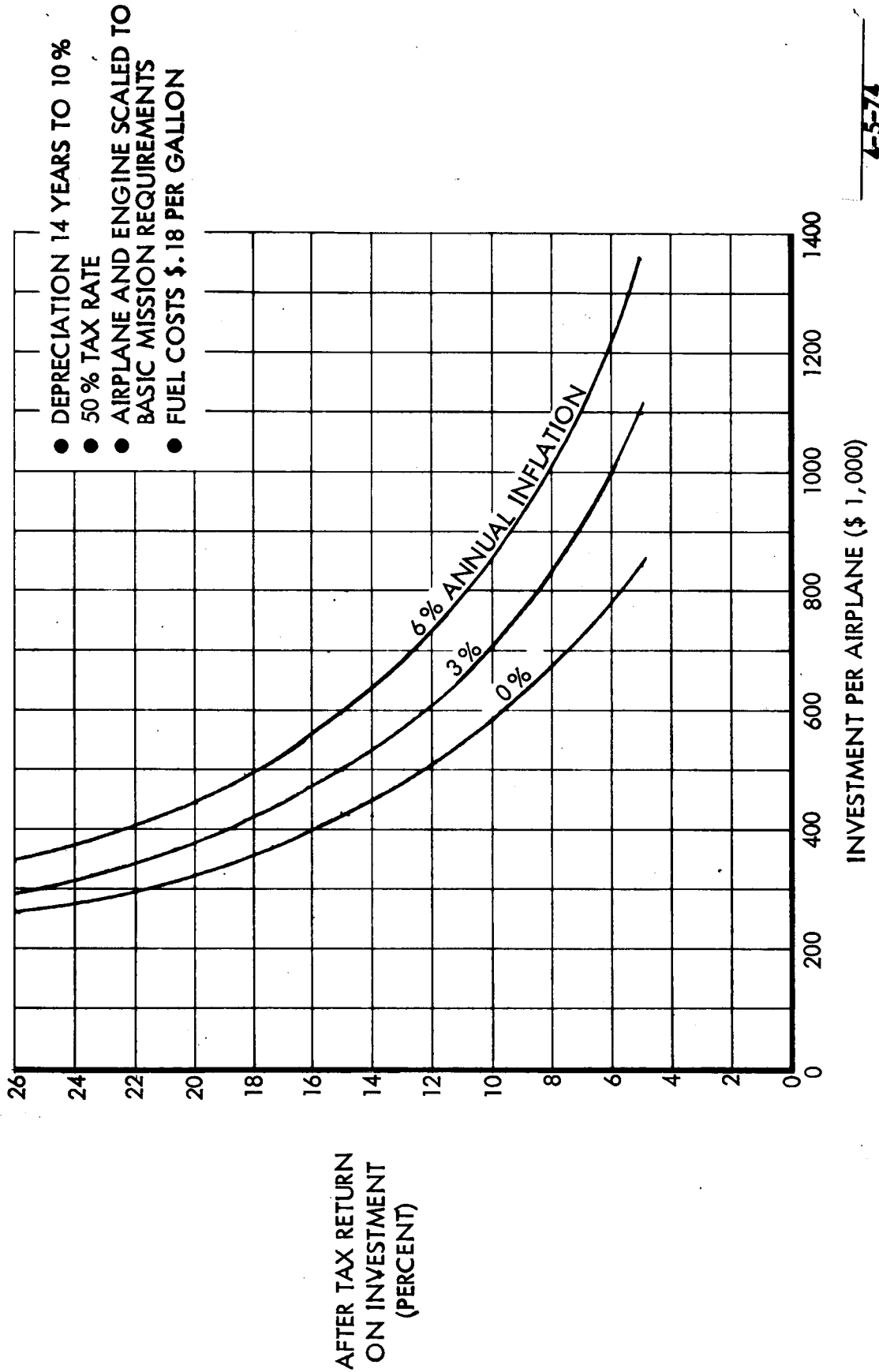


FIGURE VI-3

reduces the labor to remove and replace those units for engine repair and reduces the cost of propulsion system spares.

c.. Basic Engine

The importance of engine price in the total cost of airplane ownership was recognized in earlier economic evaluations. Since then, extensive efforts have been and are being devoted by NASA and the industry to reducing engine price. These efforts cover the whole spectrum of possibilities from advanced design, material, and fabrication technology programs to shop cost reduction suggestion programs. The results of the current study verify the need for extensive effort in this area, and may be interpreted to justify increased emphasis on first cost reduction in certain engine parts. Figure VI-4 shows that the direct operating cost reduction (including depreciation) brought about by an assumed 250,000 dollar reduction in the price of the STF-429 engine. Note that both the initial investment and the continuing maintenance cost will be reduced. The direct operating cost sensitivity to other major propulsion system variables is shown in Figure VI-5.

2. Continuing Cost of Maintenance

The continuing cost of maintenance can be reduced greatly in the design and development process by considering maintainability and reliability as fundamental design tasks of equal importance to safety and performance. The following items are considered most important to reaching the objective of lower maintenance cost.

PROPULSION SYSTEM COST IMPACT

DIRECT OPERATING COST
CENTS/SEAT MILE

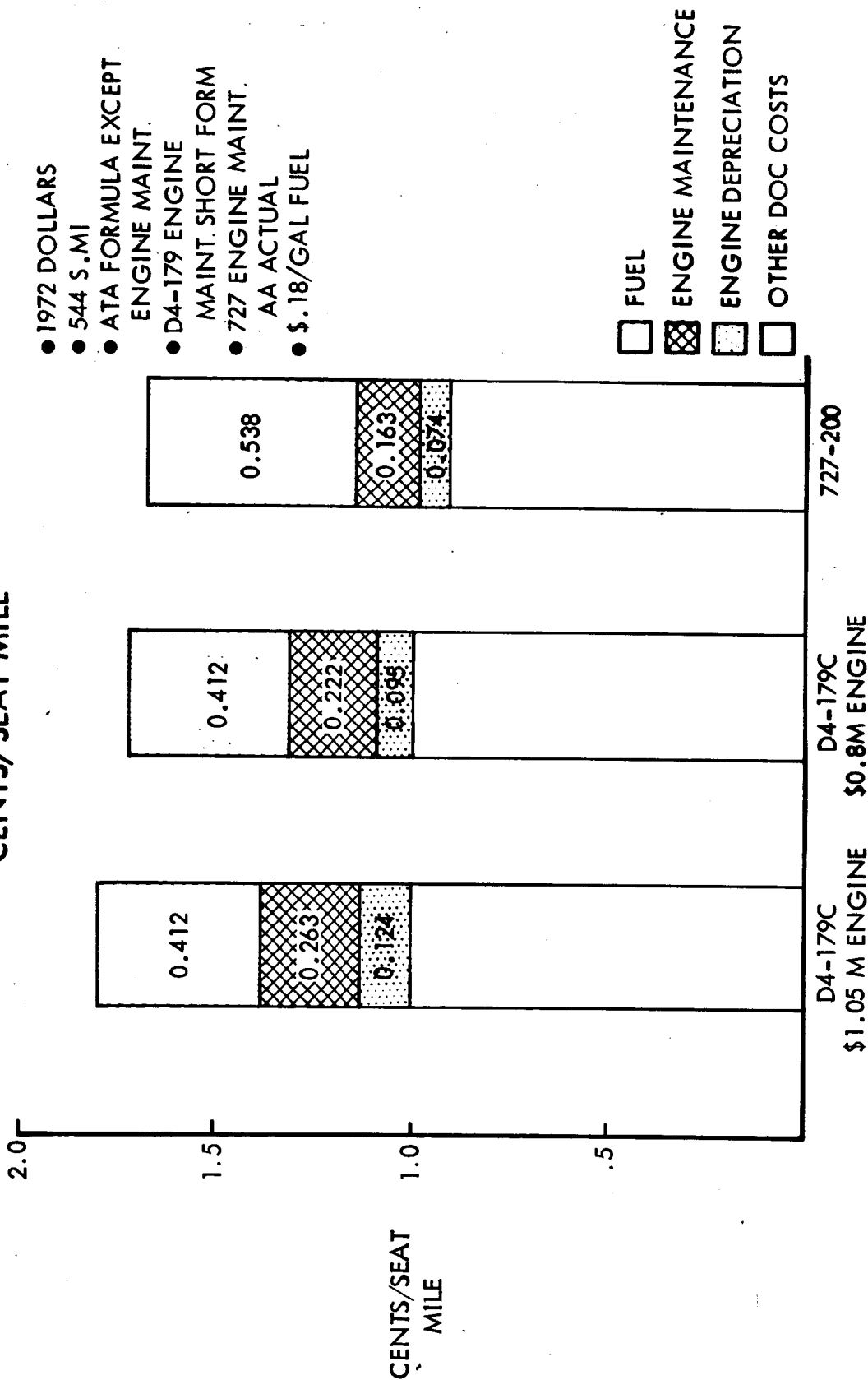


Figure VI-4

5/2/74

DIRECT OPERATING COST SENSITIVITY TO PROPULSION SYSTEM VARIABLE

D4-179C/STF 429

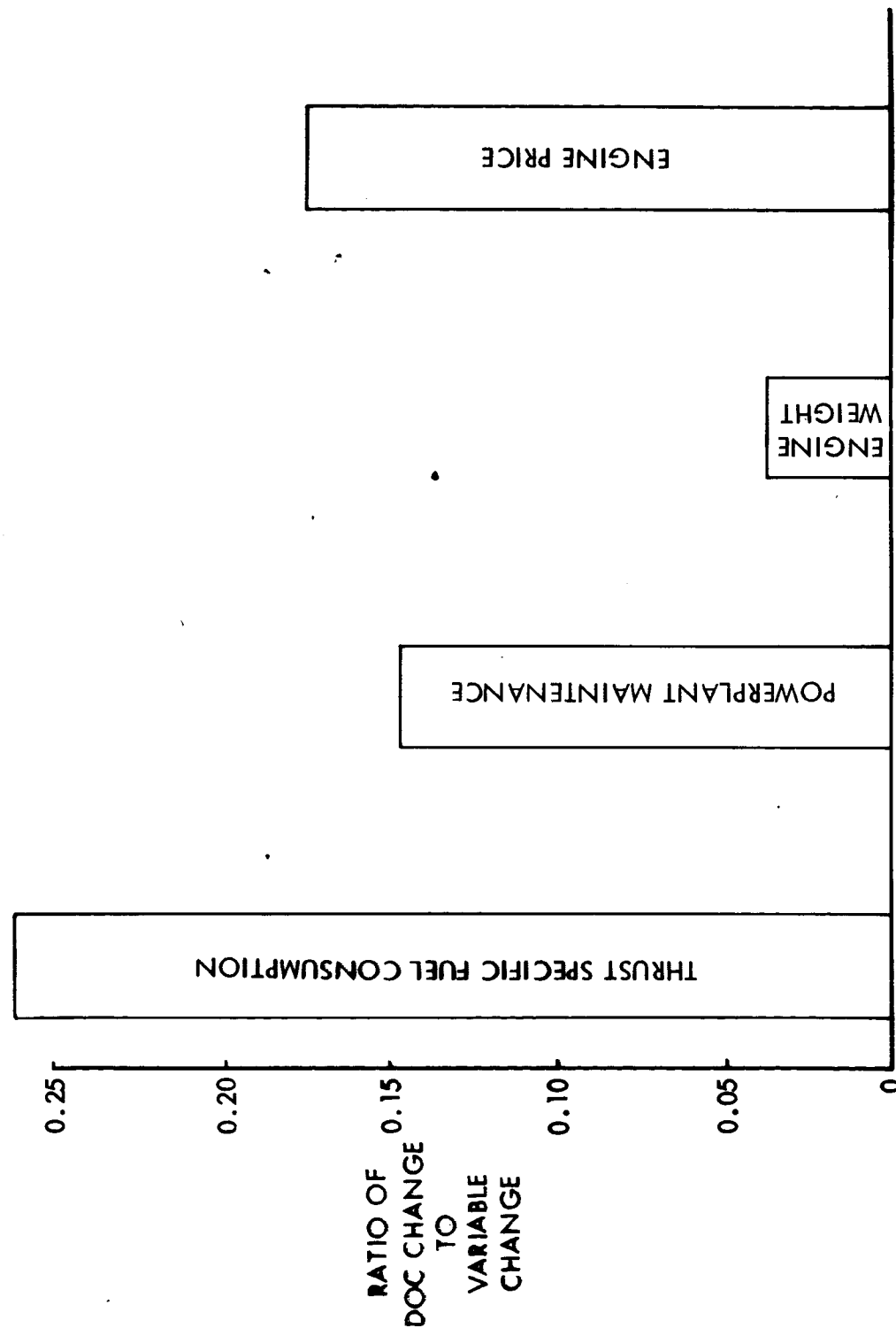


FIGURE VI-5

a. Engine/Installation

The design of the power plant installation should consider more effective troubleshooting, accessibility and facility of component change out by line maintenance. Care should be taken that the modular maintenance provisions designed into the basic engine by the engine manufacturer are not rendered useless by the power plant installation. Whenever possible locate basic engine and installation accessories on the fan case where they don't **interfere with** such components as the variable vane linkage and actuators and service bleed ports and improve on-wing basic engine modular replacement.

The development and use of automatic test equipment has enabled airlines to improve reliability and safety records while reducing unit maintenance costs especially in the troubleshooting area. A recommended area of development in the power plant system is condition monitoring equipment, sensors, data processing and analysis, and selection of parameters.

1. Basic Engine/Installation - Labor Costs

The build-up and tear-down of the airframe manufacturer's components installed on the basic engine in preparation for installation on the aircraft or in preparation for repair of basic engine modules accounts for a significant direct labor cost.

Using the estimated 30 manhours for teardown and 140 manhours for buildup of the QEC and assuming a mature engine removal rate of 0.50/1000 engine flight hours, the direct shop labor cost in 1972 dollars expended on the 100 airplane fleet flying 7.88 hours per day per aircraft is as follows:

$$\begin{aligned} \$/\text{YR} &= \frac{\$7.00}{\text{MH}} (30 \text{ MH} + 140 \text{ MH}) \times \frac{0.50 \text{ Removals}}{1000 \text{ EFH}} \times 3 \text{ Engines} \times \frac{7.88 \text{ FH}}{\text{A/C Day}} \\ &\times 100 \text{ A/C} \times 365 \text{ Days} = \$513,000/\text{YR} \end{aligned}$$

The above cost increases to approximately \$550,000 per year when material costs are included. For a new engine these costs can double during the first five years due to higher removal rates as a result of introductory problems both with the new engine and with airline maintenance people becoming familiar with the engine.

Recommended areas of future development are methods of installing inlets, side cowl and thrust reversers on the airframe so they remain with the aircraft upon engine replacement and installation of airframe manufacturer supplied engine driven accessories remote from the basic engine so they are not removed from the engine upon engine replacement. There is also a need for development of remote drive units and long shafts for driving accessories such as AC generators, constant speed drives and hydraulic pumps and provision for engine starting.

2. Thrust Reverser

Historically the Thrust Reverser System represents approximately 6% of the total power plant direct maintenance costs and 25% of the installation maintenance costs. The system also accounts for approximately 15% of the total power plant interruption costs and 35% of the installation interruption costs.

It is estimated that the reverser system for the study airplane will require an expenditure of \$3.67/flight hour ($0.85 [SL_{78} + SM_{78} + LL_{78}] = .85 [\$1.68 + 1.80 + 0.84] = \$3.67$) of direct maintenance cost. This represents an expenditure of \$1,055,000 per year (1972 dollars) for a 100 airplane fleet flying 7.88 hours per day per aircraft. Historical data indicates this maintenance cost can be reduced approximately 50% if just a fan thrust reverser is used instead of both the fan and primary thrust reversers. Components in the thrust reverser system that contribute to high maintenance costs are the blocker doors, links and actuators. The power sources used for actuation thus far have been hydraulics, pneumatics and mechanical with hydraulics being favored.

The same components that contribute to high maintenance costs also contribute to the high interruption costs with the addition of the indicating system.

Recommended areas of future development are in the actuation systems and their power sources and in the methods of turning the air. Numbers of actuators should be kept to a minimum and improved actuator reliability should be a goal considering the high temperature environment.

Since thrust reverser maintenance and interruption costs can be reduced significantly by using one reverser per engine instead of two, new methods of improving fan thrust reverser efficiency so that the primary thrust reverser can be eliminated or methods of installing one thrust reverser to turn both the fan and primary air should be developed.

b. Basic Engine

The most significant continuing cost related to the basic engine is the shop maintenance cost. Task I and II of this study have provided an improved understanding of the relative importance of the various elements of engine maintenance cost. This improved understanding can be applied to guide technology efforts to reduce the maintenance cost of future engines.

A sensitivity analysis of the maintenance cost elements of the STF429 was conducted to provide a convenient summary of the relative importance of these elements. The labor manhours per repair, mean time between repair, maintenance material cost per repair, and the prime high cost parts price of each major module were arbitrarily varied and the resulting effects on total engine maintenance cost were calculated using the method described in Section IV. The results are presented on Table VI-5 in terms of the percent change in total cost resulting from a 10% change in an element. The HPT is by far the most sensitive module in the mean time between repair, material cost per repair, and price categories, and is about average in the manhours per repair category. Therefore, it should receive the highest priority in directing technology efforts to reduce maintenance cost. The LPT and HPC module are the most sensitive in the manhour per repair category and rank relatively high in the other categories, so they should receive second highest priority. Some of the lower sensitivity elements may also be worthy of consideration if particularly large improvements are potentially available.

In evaluating an idea for improving one of the elements of maintenance cost, it is important to consider its effect on the other elements as well. It is possible that an improvement in one element will be offset by changes in one or more of the others. For example, an advanced turbine blade material might improve blade life sufficiently to increase the mean time between repair of the HPT module by 10%. But, if this material causes the price of the module to increase by more than 11% ($10 \times \frac{3.4}{3.1}$ from Table VI-4, the net result will be an increase in maintenance cost.

Specific technology recommendations for maintenance cost reduction are discussed by module as follows.

1. HP Turbine Module

Possible approaches to reducing maintenance cost in the HPT include reduced number of stages, lower aspect ratio airfoils, reduced solidity, and increased parts life.

There are several existing NASA programs working in the area of reduced number of turbine stages, both in the HPT and LPT. These programs should result in minimum cost turbines consistent with performance requirements, resulting in a direct improvement in maintenance cost by reducing the number of parts replaced. However, special attention must be given to these areas in order to avoid the possible degradation of turbine MTBR which could result from the higher temperatures and higher tip speeds that are likely to evolve.

Lower aspect ratio vanes and blades would reduce the number of airfoils required at a given solidity level, and reduced solidity would provide a further reduction. Since the price of a complex cooled airfoil is relatively insensitive to aspect ratio, these changes would result in lower cost turbines and a significant reduction in maintenance cost as

indicated by the sensitivity factors on Table VI-4. Reduced aspect ratio may also provide improved MTBR because the larger airfoil cross-section that results should be more resistant to foreign object damage. Effort in reduced aspect ratio and solidity is recommended, but it must be accomplished with minimum degradation of turbine performance to avoid fuel cost penalties that could offset the maintenance cost advantage.

There are extensive technology programs devoted to improving the life of turbine airfoils by means of improved cooling and advanced materials. However, these efforts are somewhat frustrated by a lack of reliable information on the reason for scrapping turbine airfoils in mature engines in airline operation.

2. LP Turbine and HP Compressor

The manhours per repair required in the LPT and HPC can be reduced by reducing the number of stages and by incorporating design features which reduce the effort required to disassemble, inspect, repair and reassemble the modules.

The low velocity ratio turbine technology programs that are in being will provide the information to permit minimization of the number of stages consistent with work, speed and elevation demands which are dictated by the rest of the engine. It is recommended that these programs be directed to include improved MTBR as a design objective.

High stage loading compressor technology programs are also in being and will produce the information needed to minimize the number of stages required for a given compressor pressure ratio. It is recommended that these programs be directed to improve, or at least avoid compromising, the other factors which are important to maintenance cost. For example, high tip speeds should be combined with a rotor structural design which is relatively

insensitive to unbalance and which minimizes balance shift to reduce the labor required to assemble and balance the engine. Airfoils with extremely sharp thin leading and trailing edges should be avoided because of their susceptibility to foreign object damage.

Design features, such as modular assembly, replaceable rubstrips, axially split cases, etc., which reduce maintenance labor requirements have been incorporated in the latest generation of turbofan engines. However, additional improvements are both possible and desirable. For example, individual blade locks should be eliminated wherever possible, and the number of flanges and bolts should be minimized. Such improvements are generally in the design objective category rather than the technology category, but it is possible to gain experience with them in the course of a component technology program.

3. Combustor

Combustor technology programs are sufficiently aware of the importance of combustor exit temperature profiles to the life of the HPT parts. This is by far the most significant contribution that the combustor can make to the reduction of engine maintenance cost. However, it is recommended that the repairability and MTBR characteristics of advanced technology combustors be emphasized to avoid possible compromise of these characteristics relative to current engines. For example, the choice of a new liner material or cooling configuration should consider its crack propagation and weld repair properties.

4. Controls

Advanced engine controls, which feature automatic power management, are expected to eliminate overspeed and overtemperature excursions, and to reduce the requirement for engine trim runups. Automatic power management can also reduce fuel consumption and the gross weight of the

airplane for a given payload-range, which will result in the lowest possible time at high engine power settings. These improvements reduce the rate of hot section damage, with consequent savings in maintenance cost. Advanced controls can contribute further to maintenance cost savings by providing improved troubleshooting, replaceability and repairability in the control units themselves. It is recommended that control technology programs strive for an optimum balance of these characteristics with their usual requirements for accuracy, reliability and low cost.

% CHANGE IN TOTAL MAINTENANCE COST FOR 10% CHANGE IN:

MODULE	MANHOURS	MEAN TIME	MAINT. MATERIAL COST
	PER REPAIR	BETWEEN REPAIR	PER REPAIR OR MODULE PRICE
FAN/LPC	0.1	1.0	0.9
HPC	0.5	1.5	1.0
DIFFUSER	0.1	0.2	0.1
COMBUSTOR	0.4	1.0	0.6
HPT	0.3	3.4	3.1
LPT	0.5	1.6	1.1

-313-

Total Maintenance Cost Sensitivity - STF429

TABLE VI-5.

3. Dispatch Reliability Costs

a. Starting Systems

The 727 historical experience indicates that the starting system interruption costs are approximately \$17 per 100 departures. This totals about \$40,000 per year for a 100 airplane fleet with 630 departures per day. This cost doesn't tell the whole story because start problems are primarily found after the aircraft is loaded with passengers and ready to leave the gate so a delay at this time has a detrimental effect on goodwill. To reduce the length of delays caused by a faulty start valve, a manual override is provided on all aircraft which can be operated without opening the side cowl. Some of the causes for faulty start valve operation are contamination from dirty bleed air, valve body erosion from high temperature air, damaged or frozen linkage and worn electrical connector and in-operative solenoid.

The starter is also a high contributor to delays. The primary problem areas are failure of the centrifugal switch and shaft failure.

b. Engine Instrumentation

Historical data indicates that engine instrumentation makes a significant contribution to delays. On the 727 approximately \$30 per 100 departures can be identified as interruption costs probably due to instrumentation problems. This would total approximately \$70,000 per year on a fleet of 100 aircraft. Some of the primary problems are oil pressure transducer, engine pressure ratio system, oil quantity system, and airborne vibration monitoring system.

c. Engine Systems Components

The primary causes for high interruption costs in the basic engine system components area are the fuel control, fuel pump and ignition ignitors and exciters. The total interruption cost is approximately \$75 per 100 departures which represents approximately \$170,000 per year on a fleet of 100 aircraft. Identification of specific problem areas in these components will require further study such as reviewing shop findings and

discussion with suppliers.

d. Thrust Reverser

The 727 historical experience indicates the thrust reverser system interruption costs are approximately \$60 per 100 departures. This totals about \$140,000 per year for a 100 airplane fleet with 630 departures per day. These interruptions are due primarily to problems in actuation, linkage, indication and doors. The environment particularly for the primary thrust reverser is very harsh e.g.: high temperatures and gas velocities. As noted in paragraph IV.D.2., development work on this system could contribute greatly in reducing maintenance costs as well as interruption costs.

e. General

As noted in Section III F. "Dispatch Reliability" the data indicates that Mechanical dispatch Reliability may be a function of flight length. The reasons for this trend are not within the scope of this contract, but would be worthy of future study.

4. Fuel Costs

The cost for fuel is generally assumed to be a function of the specific range of the aircraft and the price of fuel. Knowing these two factors, the cost for fuel per flight hour can be readily determined. However, the specific fuel consumption of the engine does not stay fixed with time. The maintenance programs conducted on the aircraft as well as the engine dictate the relative loss in aircraft specific range characteristics with time. Past experience has indicated that the higher performance engines have lost specific fuel consumption performance at a more rapid rate than early lower performance engines.

The engine and its installation are both sources of the observed performance loss with time. The maintenance costs discussed herein reflect this gradual loss accepted as economically justified based on low and almost constant cost of fuel. The rapidly increasing cost for fuel suggests that propulsion system maintenance cost could be justifiably increased if recovery of fuel consumption performance could be achieved. The technology required to identify the cause(s) of the performance loss and economic means of recovery does not exist today.

a. Power Plant Installation

The design of the power plant installation is generally directed at maximizing installed engine performance and aircraft performance. Installation losses are encountered on all engines from bleed and horsepower extraction to drive the various aircraft subsystems. The increases in specific fuel consumption due to these off-takes is roughly 5%. At the same time, the installation involves other losses

due to nozzles, inlets, fan air bleed for cooling, thrust reverser seal leakage etc. The maintenance of these items may and may not correct problems which affect performance. More effort in original design to insure that performance critical components can be properly maintained is recommended.

b. Basic Engine

The significance of the thermodynamic cycle parameters (bypass ratio, overall pressure ratio, combustor exit temperature, etc.) and the aerodynamic design of the fan, compressor, and turbine to the fuel consumption characteristics of an engine are well known. These areas have been the subject of extensive studies, R&D programs, and development efforts, and they are receiving renewed emphasis by both NASA and the industry in response to the fuel shortage. A related area that has received relatively little attention however, is the fuel consumption characteristics of an engine as it accumulates time in airline service. AA data indicates that the fuel consumption of its engines has increased by several percent since they were delivered. This deterioration has occurred despite extensive repair and replacement of parts which is evidenced by the maintenance cost data in Section III. The nature of the fuel consumption deterioration is not well understood by either the airlines or the engine manufacturer. It is recommended that the following technology improvements be pursued to minimize the effect of such deterioration in the future;

1. Analytically and experimentally determine the causes of fuel consumption deterioration in currently operational engines,

and the most economical and expeditious means for recovering the loss.

2. Design and test engine parts and components to determine the importance of various design features and the mechanisms associated with deterioration.

3. Define design criteria applicable to future advanced engines to insure minimum deterioration and economical restoration.

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15. Supplementary Notes Project Manager, James F. Dugan, Jr., Wind Tunnel and Flight Division, NASA Lewis Research Center, Cleveland, Ohio.					
16. Abstract The results of an airline study of the economic effects of propulsion system technology on current and future transport aircraft are presented. This report represents the results of a detailed study of propulsion system operating economics prepared by American Airlines and its two sub-contractors, The Boeing Commercial Airplane Company and the Pratt & Whitney Division of United Aircraft Corporation. The study has four major parts: (1) A detailed analysis of current propulsion system maintenance with respect to the material and labor costs encountered versus years in service and the design characteristics of the major elements of the propulsion system of the B707, B727, and B747. (2) An analysis of the economic impact of a future representative 1979 propulsion system is presented with emphasis on depreciation of investment, fuel costs and maintenance costs developed on the basis of the analysis of the historical trends observed. (3) Recommendations concerning improved methods of forecasting the maintenance cost of future propulsion systems are presented. A detailed method based on the summation of the projected labor and material repair costs for each major engine module and its installation along with a shorter form suitable for quick, less detailed analysis are presented. (4) Recommendations concerning areas where additional technology is needed to improve the economics of future commercial propulsion systems are presented along with the suggested economic benefits available from such advanced technology efforts.					
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